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EUROMBRA

EUROMBRA WORKSHOP

11-12 July 2006

Bio-fouling in membrane systems

NTNU – Norwegian University of Science and Technology, Trondheim, Norway

Presentation handouts
Part 2

Organized by: EUROMBRA

Hosted by: NTNU
Department of Hydraulic
and Environmental Engineering

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and Environmental Engineering

Preface

AMEDEUS and EUROMBRA constitute the European cluster MBR-Network. The two consortia are two Specific Targeted Research Projects supported by the European Commission under the Sixth Framework Programme (Priority “Global Change and Ecosystems”) - duration: 01/10/2005 -30/09/2008. The focus of research in this cluster is the development of membrane bioreactor (MBR) technology for the treatment of municipal wastewater.

A central activity within the cluster is the development of a MBR-network where the aim is to promote communication and exchange of MBR-competence within Europe and the worldwide MBR-community as a whole, and contribute to developing contacts to a large group of international MBR professionals and experts. The first event within this category was the organization of the MBR-Network Workshop on Bio-fouling in membrane systems, organized by the EUROMBRA project and hosted by the Norwegian University of Science and Technology (NTNU) in Trondheim, Norway. The event was held on 11-12 July 2006.

This workshop has provided a forum for the MBR-Network partners as well as contacts and experts from the global membrane community working with bio-fouling in membrane systems. The aim of the Workshop was to promote a scientific discussion and exchange forum, where discussions were initiated by the topics outlined in the abstracts of the presentations presented in this Book of Handouts. MBR-Network desires to promote and encourage student work and studies within the activities of the cluster and student contributions related to on going studies/research on bio-fouling were therefore included in the programme. In addition to the Book of Handouts, abstracts of presentations given at the workshop have also been published – Book of Abstracts, (ISBN 82-7598-065-8)

The topic covered in this workshop is a crucial and central issue for the development of MBR technology. Understanding the fundamentals, mechanisms, implications, and remedial actions necessary with respect to biofouling is essential for the success and implementation of this technology as an alternative solution to meet the future demands and goals of municipal wastewater treatment. From this perspective the workshop has indeed contributed to a better understanding of biofouling in MBR systems even though many questions still remain.

TorOve Leiknes
Editor

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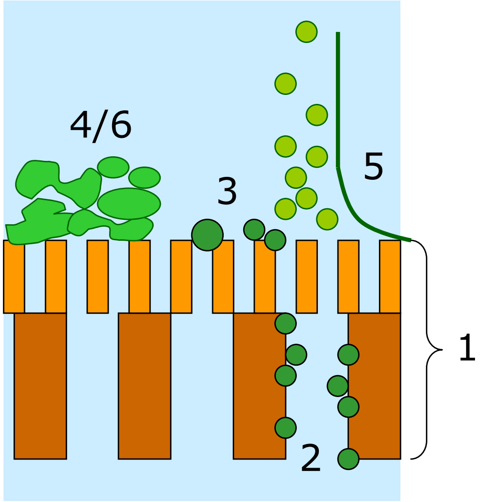
Scope of the Workshop

Gaining a better understanding of fouling in membrane systems, bio-fouling in particular

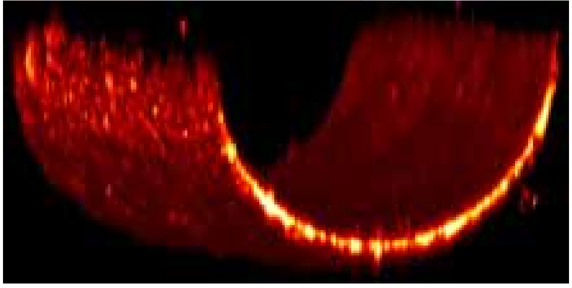


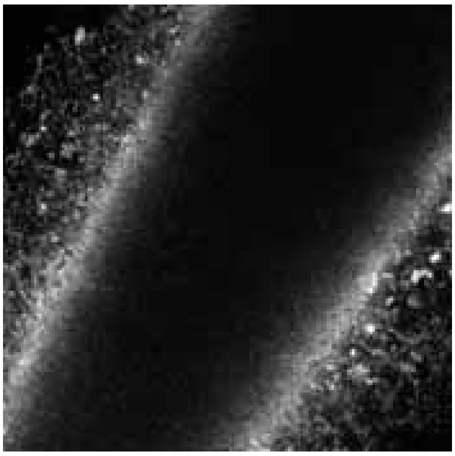
1. Membrane resistance: R_M

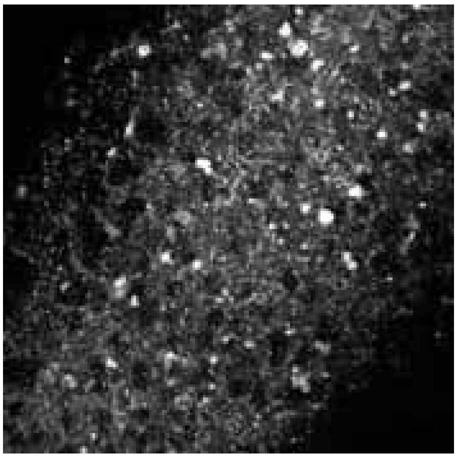
2. Adsorption / scaling: R_F
 - reversible / irreversible
3. Pore blocking / plugging: R_P
4. Cake formation: R_C
 - dead-end drift
5. Concentration polarization: R_G
 - formation of gel-layer
6. Biofouling – biofilm/EPS: R_B

Getting to grips with bio-fouling

- What s it?
- How can we determine it?
- What can we do with it?
- How can we live with it?......







Staining: **Hoechst** (binds to DNA)

MONHEIM

MBR MONHEIM

OPERATION

OPERATION WITH COLD TEMPERATURES

TEMPERATURES

Overview

- Local Terms of the MBR Monheim
- Requirements
- Design of the MBR
- Operating Conditions
- Operating Results
- Permeabilities
- Discussion

  Reasons, Consequences, Futher Needs

Introduction

Name:	Detlef Wedi
Profession:	Civil Engineer
Employer:	Engineering& Consulting Office ATM
Main Activities:	Design & Optimisation of WWTs Research & Development Introduction and Testing of New Processes Expertises, Studies Mikrobiology, Application of Genprobes

Geographic situation

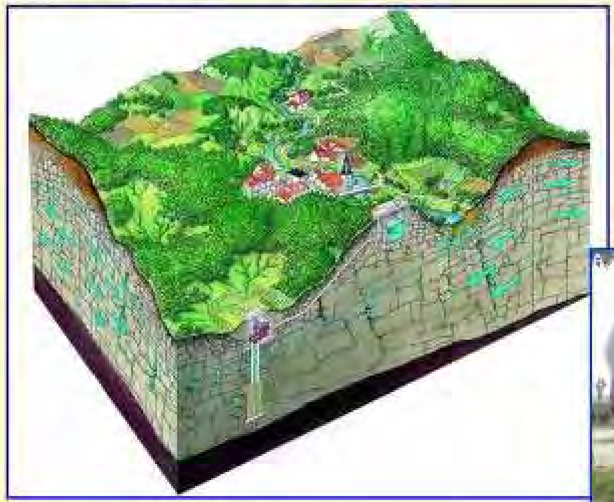
City of Monheim, Bavaria, 520 m above sea level

Geographic situation

Rivulet
„Upper Gailach"

Gailach Infiltration

Geographic situation



Karst formation

Bedrock

Demands

The requirements for the effluent quality are on a very high level.

COD	≤ 75 mg/l
BOD_5	≤ 15 mg/l
NH_4-N	≤ 5 mg/l
$N_{tot,\ anorg}$	≤ 15 mg/l
P_{tot}	≤ 1 mg/l
susp. Solids	not detectable
The data of the hygienic parameters in the permeate must range in the order of magnitude below the guide values of the EU-Guideline for bathing waters 76/160 EWG.	

all demands for grab samples

Demands

Hygienic demands for the MBR Monheim

EG-Guideline for the quality of bathing water from 8.12.1975 (76/160 EWG)				DEMAND
Parameter	**Vol.**	**Limit value**	**Guide value**	
Total Coliforms	100 ml	10.000	500	50
Faecal Coliforms	100 ml	2.000	100	10
Streptococcus faecalis[1]	100 ml	0	100	10
Salmonella[1]	1 l	0	-	-
Enterovirus[1]	pfU/10 l	-	-	-

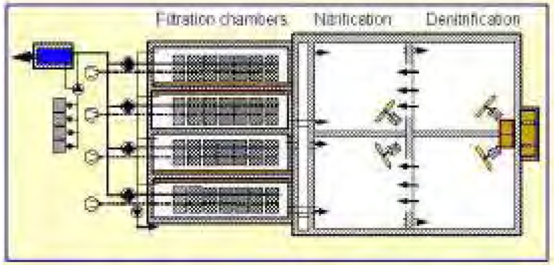
Schedule of the Pilot Project

The pilot project was supported by the Bavarian ministry for environment and accompanied by a scientific program (except 2005 - June 2006).

1997	First thoughts about a pilot project
1998	General layout of the MBR Monheim
1999/2000	Sketches and concepts
2001	Design optimisation and construction
2003	Startup in July

New Design

In 1998 the design included several new developments and up to then unproved processes.



- 1 mm Sieves, single stage
- no by-pass for the sieves
- separate membrane chambers
- new hydraulic feeding
- hydraulic separation
- chemical in-situ-Cleaning
- preventive chemical cleaning
- new mixing of chemicals
- exclusive use of H_2O_2 (alkaline cleaning)
- appropriate store for chemicals

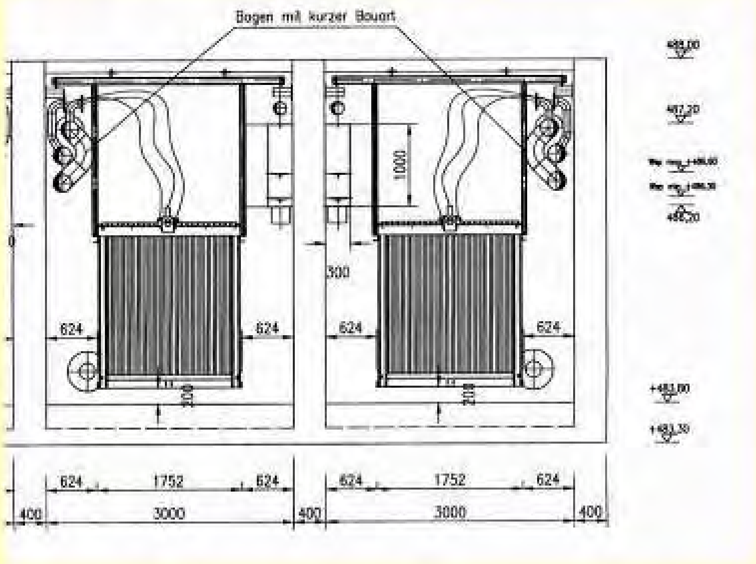
Dimensioning and Volumes

Nominal size:	9.700 PE
Design inflow:	max. 80 l/s resp. 288 m³/h
Average daily inflow:	2.400 m³/d
Aerobic tank:	2 x 340 m³
Anoxic tank:	2 x 340 m³
Membrane chambers:	4 x 75 m³
SRT_{design}:	25 – 35 d
$MLSS_{AST}$:	8-10 g/l
$MLSS_{MBR}$:	10-12 g/l
Membranes:	4 x 7 Zenon 500c, 12.320 m²
max. Flux:	23,4 l/m² h
Average Flux:	8,1 l/m² h
Design temperature:	8°C (winter)

Construction Period

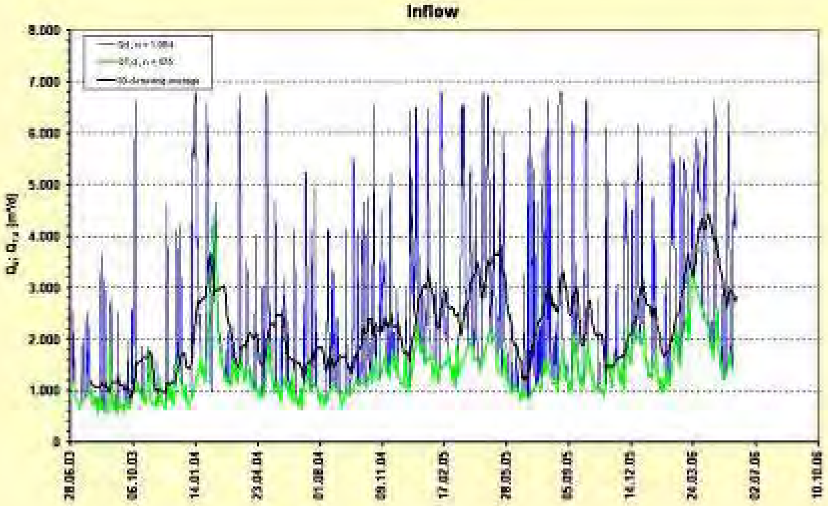
Construction Period

Membrane chambers with ZeeWeed 500c

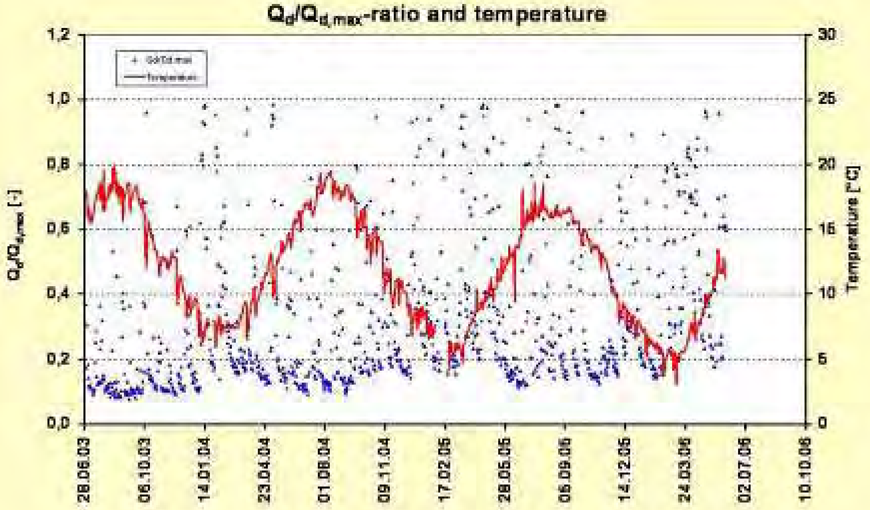


MBR Monheim, Summer 2005

Hydraulic loads



Hydraulic loads and temperatures



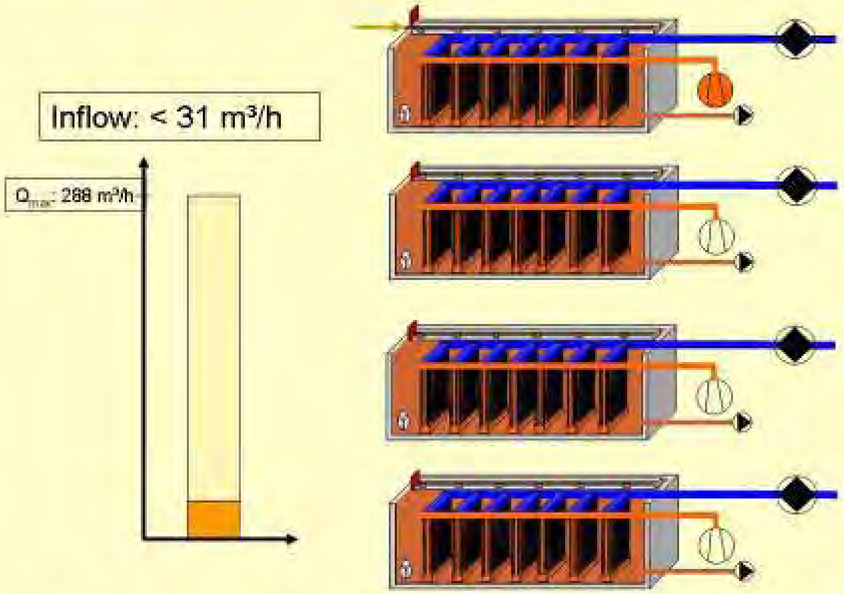
Loads and performance

There is no problem to keep the standards

		Influent	Demand	Permeate
Q	m³/d	2.214		
COD	mg/l	452	75	15
TN	mg/l	49,0	15*	7,0
NH_4-N	mg/l	29,2	5	< 0,1
NO_3-N	mg/l	0		5,3
P_{tot}	mg/l	7,2	1,0	0,7

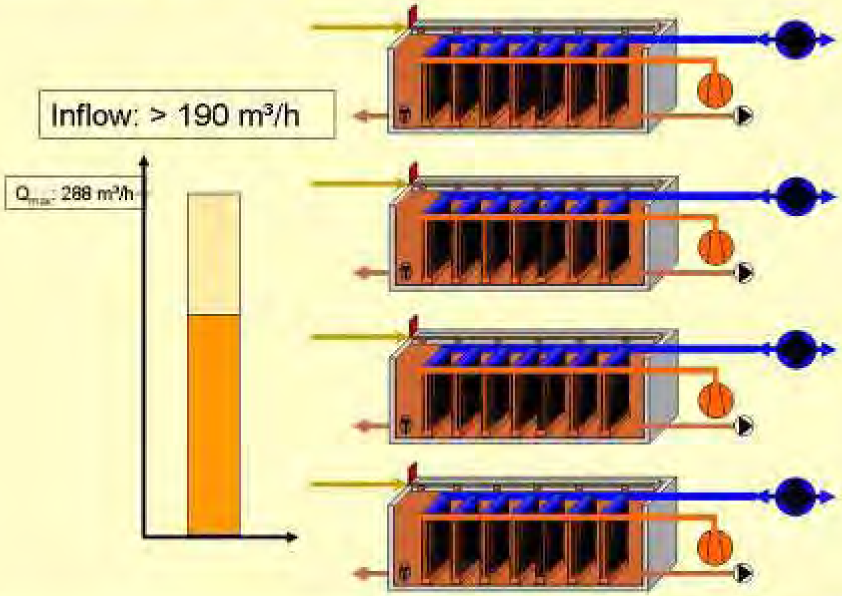
* in the effluent def. as N_{anorg}

Membrane Operation



Inflow: < 31 m³/h

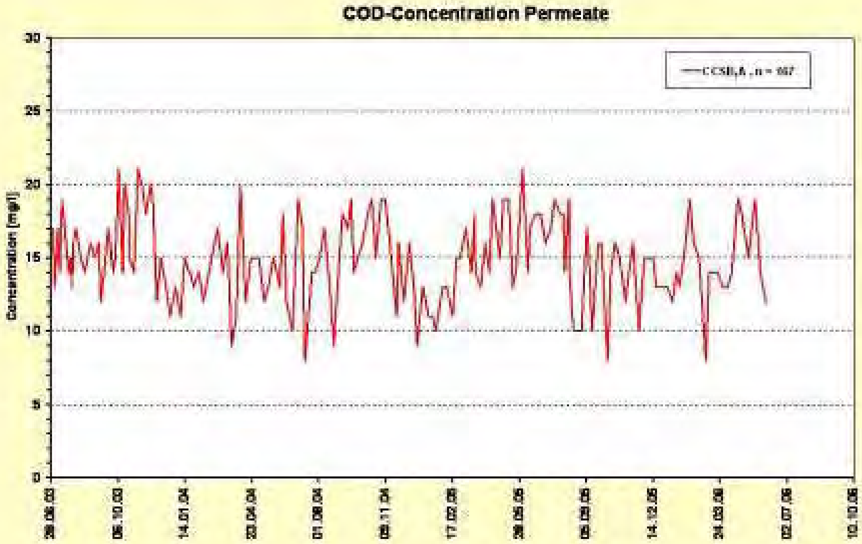
Membrane Operation



Inflow: > 190 m³/h

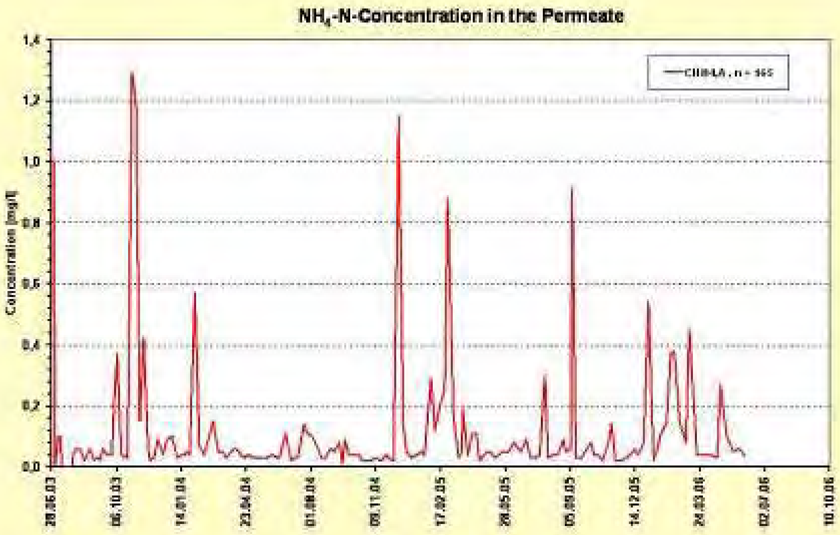
Q_{max}: 288 m³/h

Effluent Quality



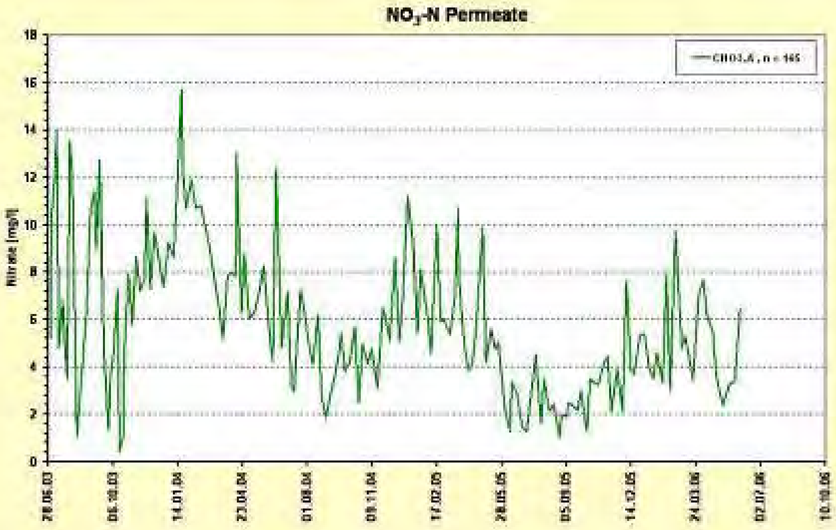
COD-Concentration Permeate

Effluent Quality



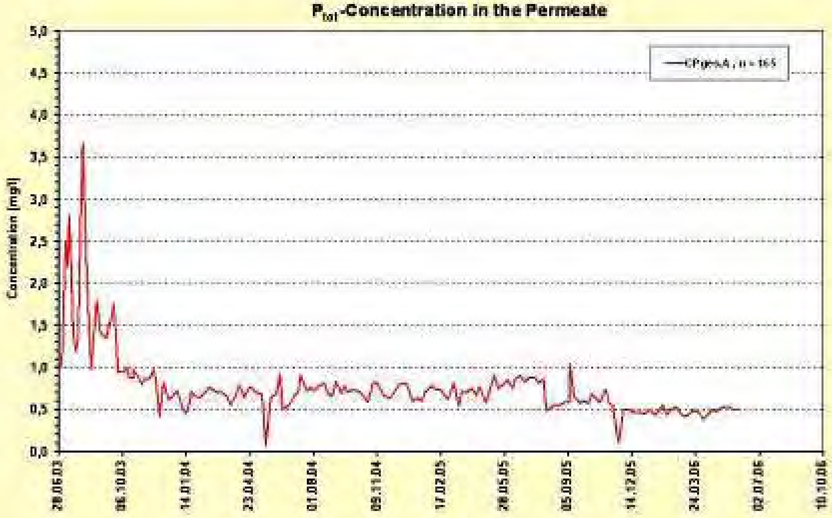
NH_4-N-Concentration in the Permeate

Effluent Quality

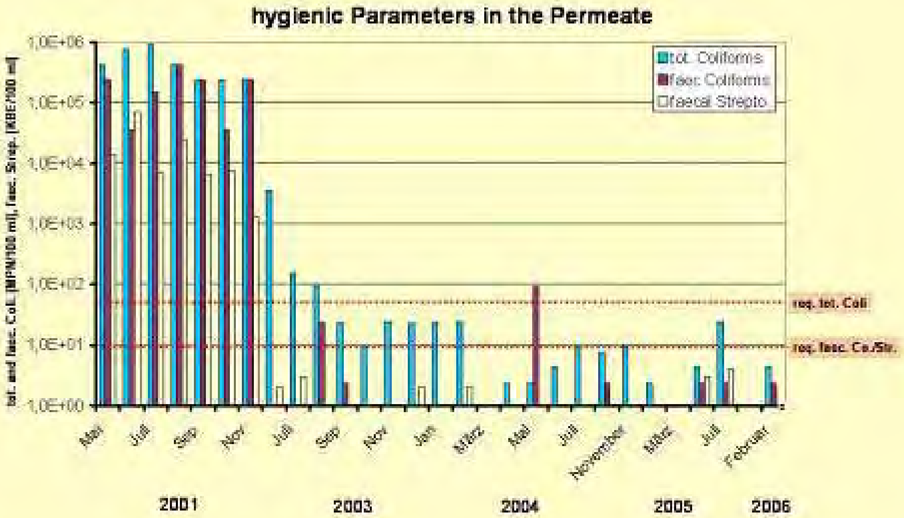


NO_3-N Permeate

Effluent Quality



Effluent Quality



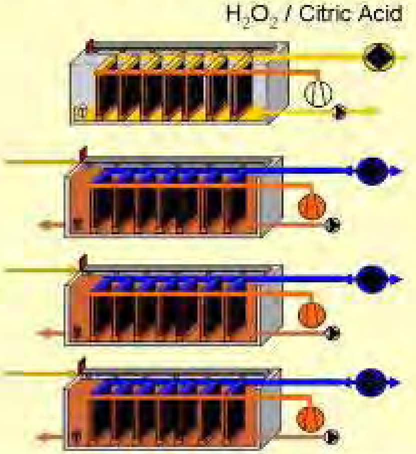
Chemical Recovery

To avoid AOX-formation in the sludge and in the effluent the use of (as we know very efficient) NaOCl is not desirable.

The WWTP Monheim was the first full scale MBR plant using exclusively H_2O_2 for chemical recovery in order to protect the groundwater, the use of NaOCl is generally not allowed.

Chemical Recovery

In intervalls of 14 days the chambers were emptied and the chemical solutions (1. H_2O_2+NaOH; 2. Citric acid + nitric acid) were pumped backwards implusively into the modules.



Chemical solutions:

H_2O_2	2000 ppm, pH 9,5
Citric Acid	2000 ppm, pH 2,0

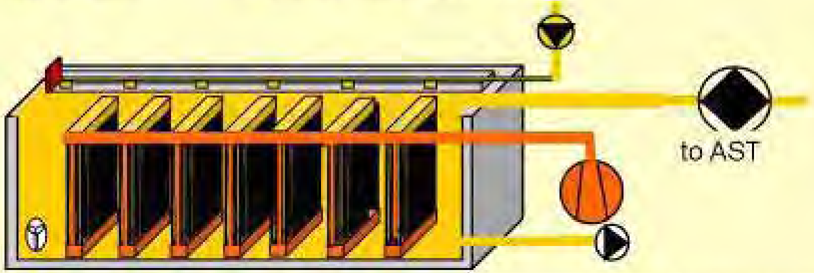
Residence time:each solu. appr. 1 h

Chemical Recovery

In intervalls of 6 months the chambers were emptied and completely filled with the chemical solutions (1. H_2O_2+NaOH; 2. Citric acid + nitric acid). The membranes stayed for one night in each solution.

Chemical solutions:

H_2O_2	5000 ppm, pH 9,5
Citric Acid	2000 ppm, pH 2,0
Residence time:	in each solution appr. 15 h



Effects with intensive cleaning

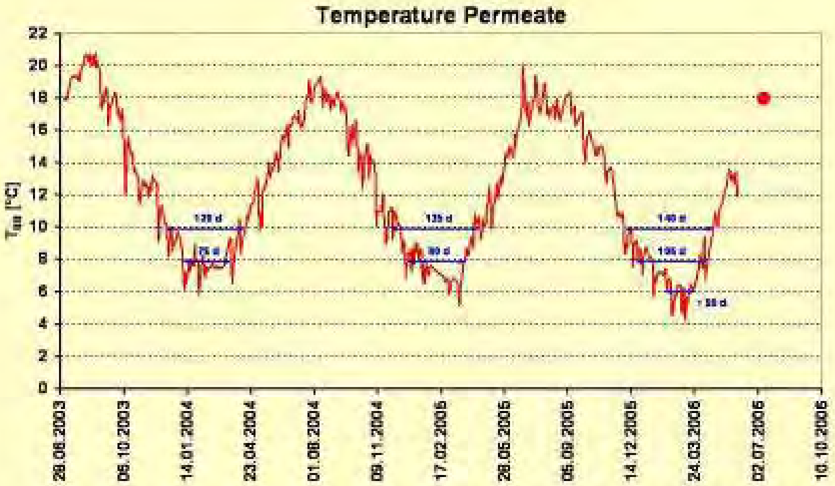
before and..

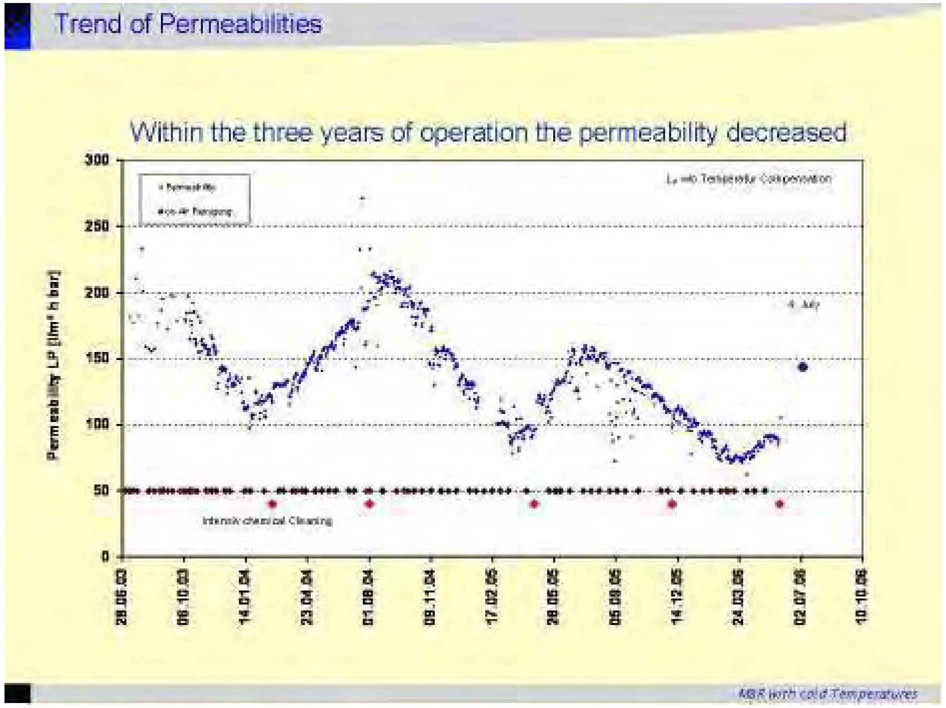
after intensive chemical cleaning

Effects with chemical cleanings

- No chemical recovery changed the actual permeability.
- In the first summer period the original permeabiliy was re-established.
- During the second winter the wastewater was very cold.
- During the third winter the wastewater was even colder.
- In the third summer period the permeabiliy dropped down.

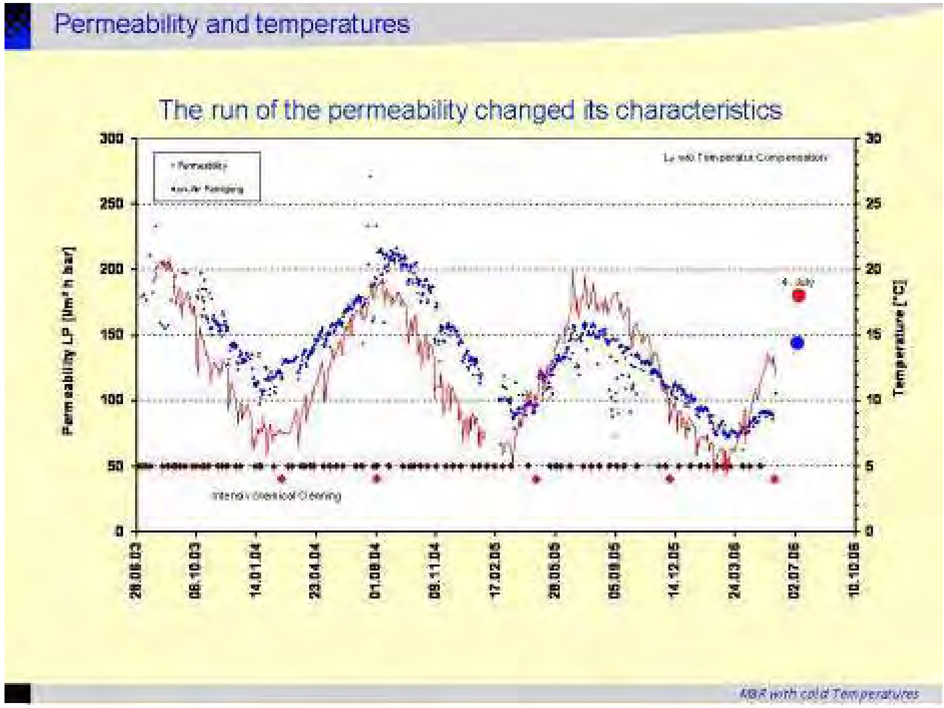
Temperatures





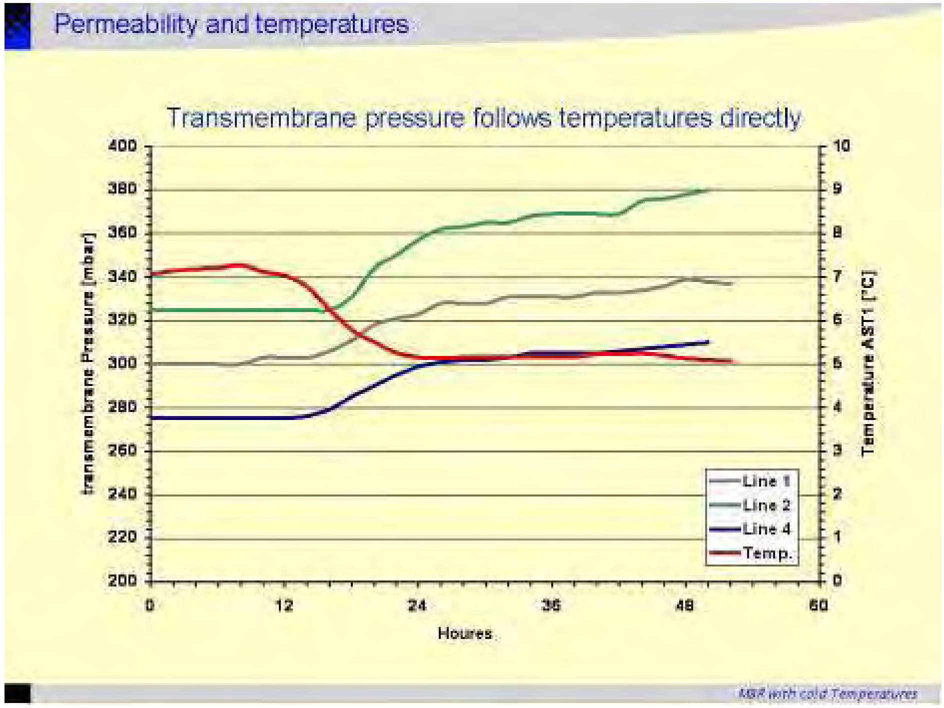
Trend of Permeabilities

Within the three years of operation the permeability decreased



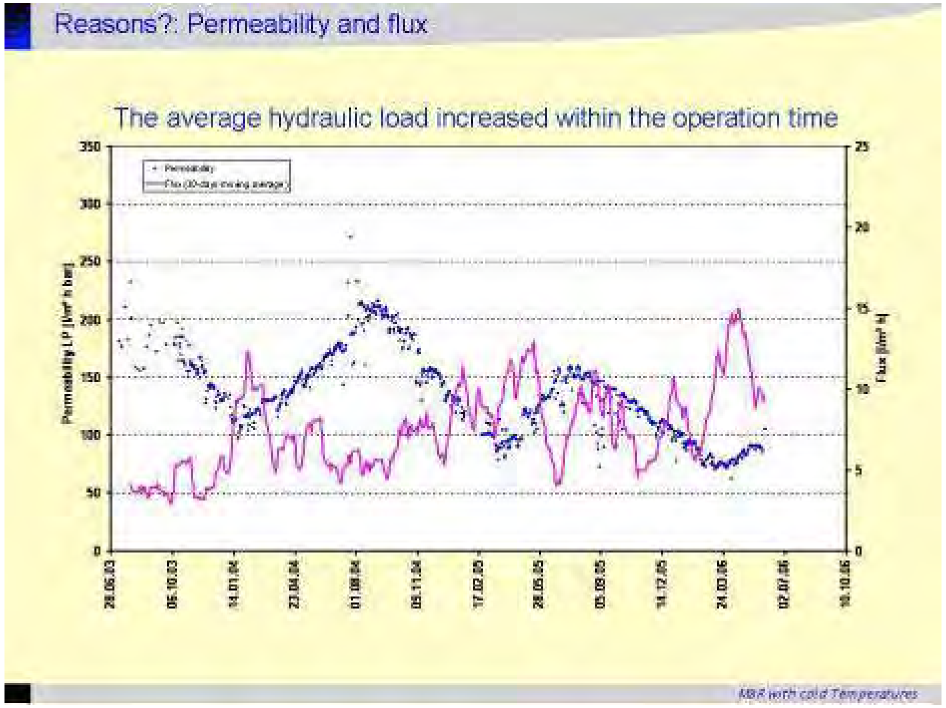
Permeability and temperatures

The run of the permeability changed its characteristics



Permeability and temperatures

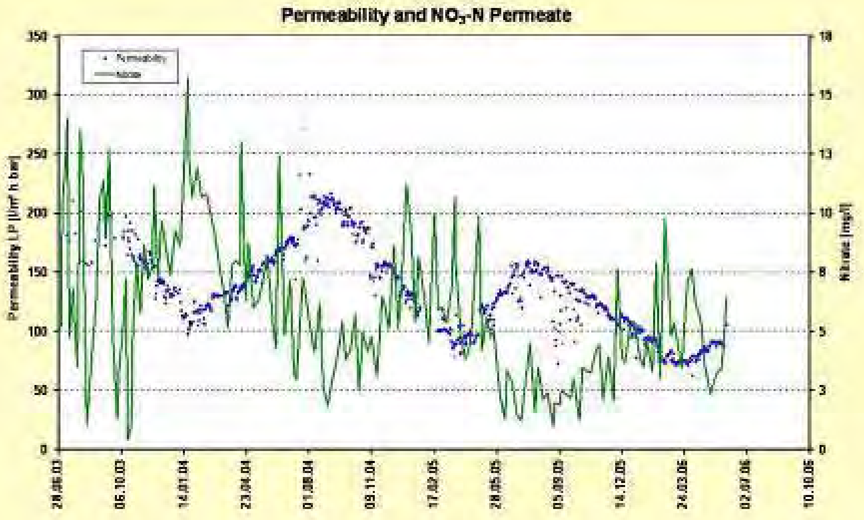
Transmembrane pressure follows temperatures directly



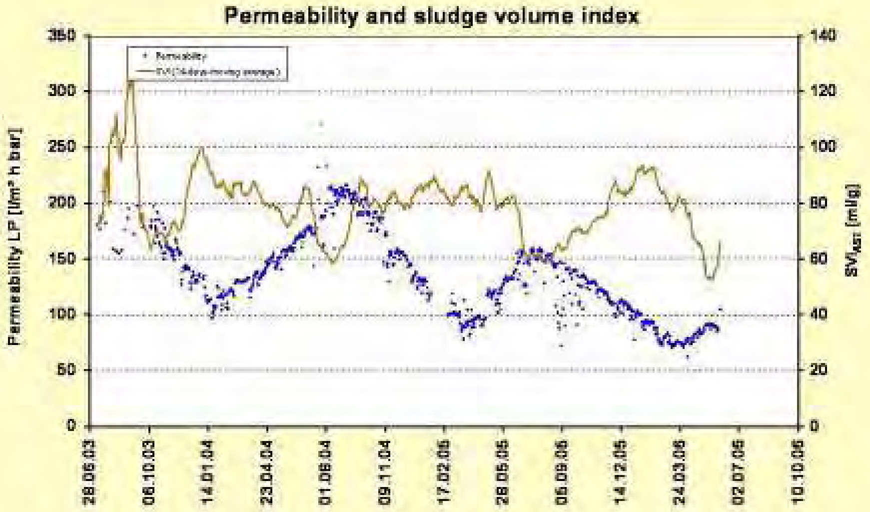
Reasons?: Permeability and flux

The average hydraulic load increased within the operation time

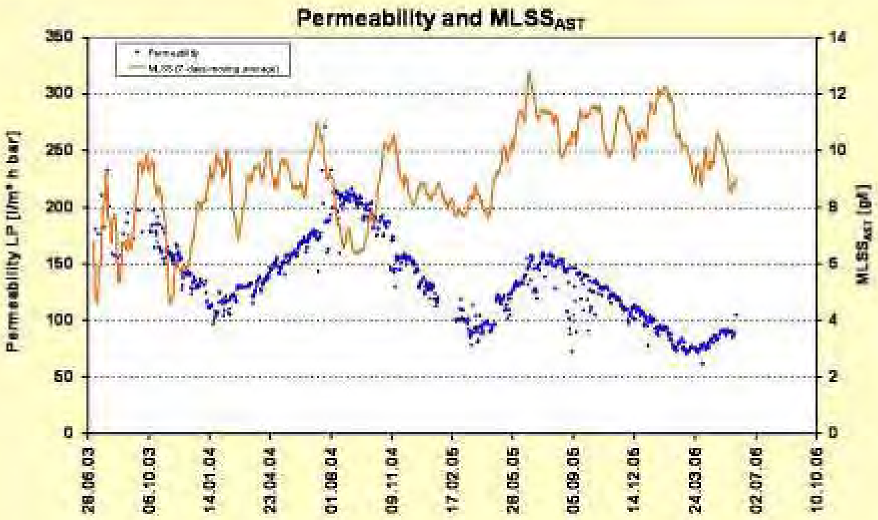
Reasons?: Permeability and nitrate



Reasons?: Permeability and SVI



Reasons?: Permeabilities and MLSS



Discussion

ASSUMPTIONS

- The chemical recovery with H_2O_2 doesn`t work sufficiently
- In spite of good recovery Membrane aging could not be avoided
- SRT (appr. 35 d) is too long, but concentations of humic substances (appr. 12 mg/l), carbohydrates and proteines (each < 1,5 mg/l) are very low
- Higher concentrations of MLSS decreases permeability
- Lower concentrations of NO_3-N decreases permeability
- The sludge characteristics (dewatering) deteriorated

Thanks for your attention!

EUROMBRA WORKSHOP
Trondheim 11-12 July 2006

Influence of biological operating conditions on sludge quality and membrane hydraulic performance of MBR

P. Grelier, A. grelot, A. tazi-Pain

Content

- ➔1. Introduction
- ➔2. Experimental
- ➔3. Results and discussion
- ➔4. Conclusion

Effluent quality

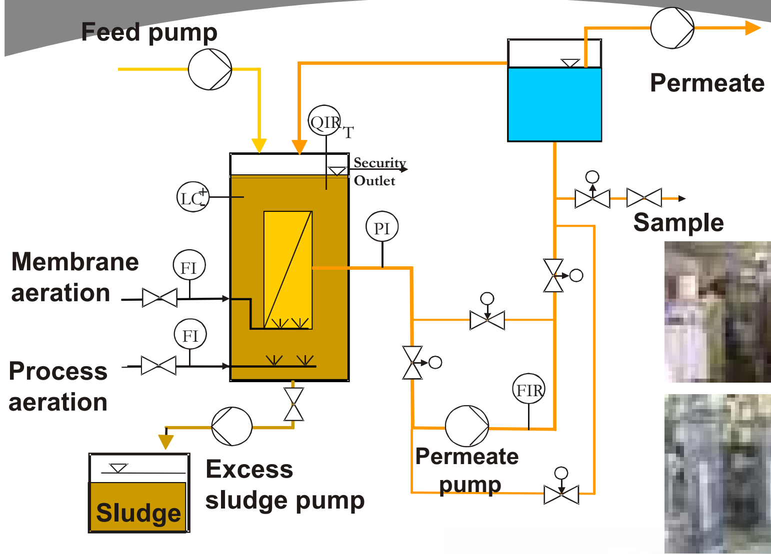
- ➔ Turbidity < 1 NTU
- ➔ BOD > 99% removal
- ➔ Generally, COD > 90% removal (refractory COD)
- ➔ Bacteria removal 5-6 log

	COD feed (mg/L)	COD effluent (mg/L)	Removal
Cosmetic industry	6,400	280	**96%**
Waste product industry	4,700	430	**91%**
Chemical industry 1	7,000	350	**95%**
Chemical industry 2	20,700	1,570	**92%**
Paper mill industry	3,300	100	**97%**
Food industry	1,020	50	**94%**
Leachates	1,000	700	**30%**

Aim of the study

- Find the best biological operating condition (membrane fouling and treatment cost)
- Influence of the sludge age on the treated water quality
- characterize the sludge quality depending on the sludge age
- Determine the influence of the sludge age on the membrane performances
- Compare the impact of the sludge age and the sludge concentration on the membrane performances
- Develop a laboratory protocol to predict the fouling potential of the sludge

Scheme of the pilot



Feed pump

Permeate

Sample

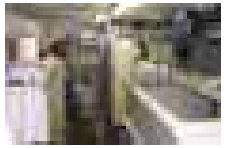
Membrane aeration

Process aeration

Sludge

Excess sludge pump

Permeate pump



Operating conditions

Mean feed water quality

Parameter	COD (mg/L)	Nt (mg/L)	N-NH$_4^+$ (mg/L)	TSS (mg/L)	pH
Municipal waste water	458	59	41	192	7.7
Food industry waste water	4676	-	-	1230	5.8

Biological operating conditions

Parameter	SRT (days)	HRT (hours)	Volumetric loading rate (kgCOD/m^3/day)	F/M ratio (kgCOD/kgMLSS/d)	Sludge concentration (g/L)
Municipal waste water	8 40	4.5 12	0.9 2.7	0.1 0.3	3.2 7.7
Food industry waste water	15 40	50 20	1 3	0.1 0.3	10.5

Analyses

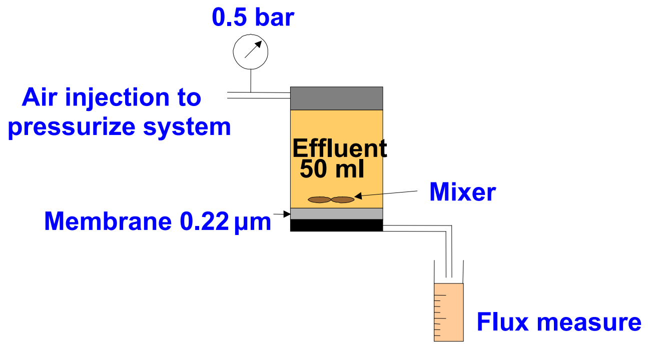
- **Waste water – Treated water**

BOD, COD, and Ammonia

- **Sludge**

- Total suspended solids
- Protein concentration in supernatant (Methode of Dubois and all)
- Polysaccharides concentration in supernatant (method of Nielsen and Griebe 1995)
- Fitrability Test

Filtrability test



0.5 bar

Air injection to pressurize system

Effluent 50 ml

Mixer

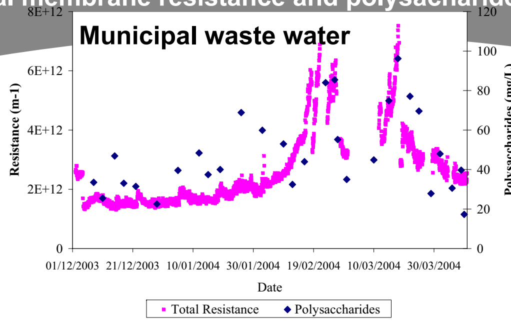
Membrane 0.22 µm

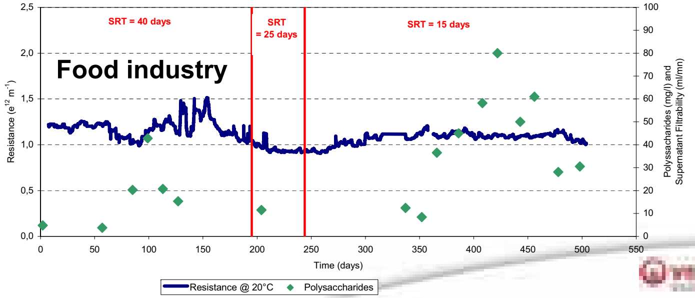
Flux measure

Quality of the treated water

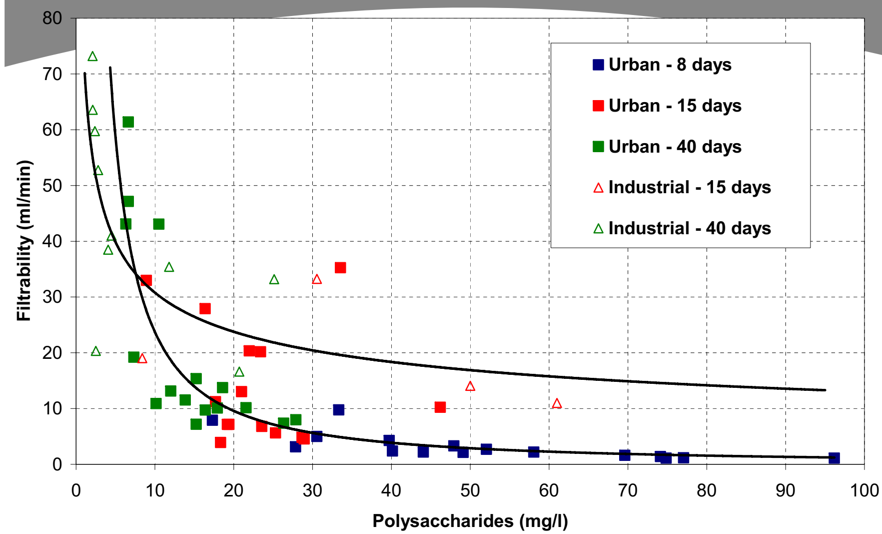
	SRT 8 days		SRT 15 days		SRT 40 days	
	Phase I	*Phase II*	*Phase I*	*Phase II*	*Phase I*	*Phase II*
F/M ratio [kgCOD/kgMLSS/d]	0.3	0.3	0.2	0.2	0.1	0.1
Sludge concentration [g/L]	3.2	7.8	4.9	6.8	7.7	7.3
HRT [h]	12	4.5	12	6.0	12	12
COD removal [%]	96	**90**	96	95	97	96
NNH4 removal [%]	98	**14**	99	98	98	98

Total membrane resistance and polysacharides results





Filtrability as a function of polysaccharides concentration



Sludge characterization

Resistance :

$$R = \frac{\Delta P \times \Omega}{\mu \times Q} \text{(en m}^{-1}\text{)}$$

with :

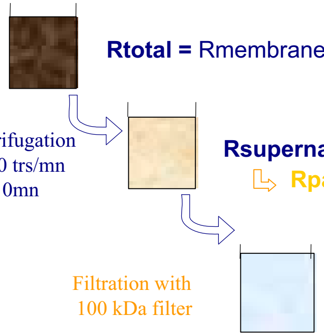
ΔP = 0.5 bar= 0,5.10^5Pa

$\Omega = \Pi \times R^2 = \Pi * (47.10^{-3})^2$ m²

$\mu_{eau} = 1.10^{-3}$ Pa.s

Filtration with 0,22 µm filter

The resistances are determined with the filtrability test



Rtotal = Rmembrane + Rparticulate + Rcolloidal + Rsoluble

Centrifugation
3500 trs/mn
10mn

Rsupernatant = Rtotal - Rparticulate

↳ **Rparticulate =** Rtotal - Rsupernatant

Filtration with
100 kDa filter

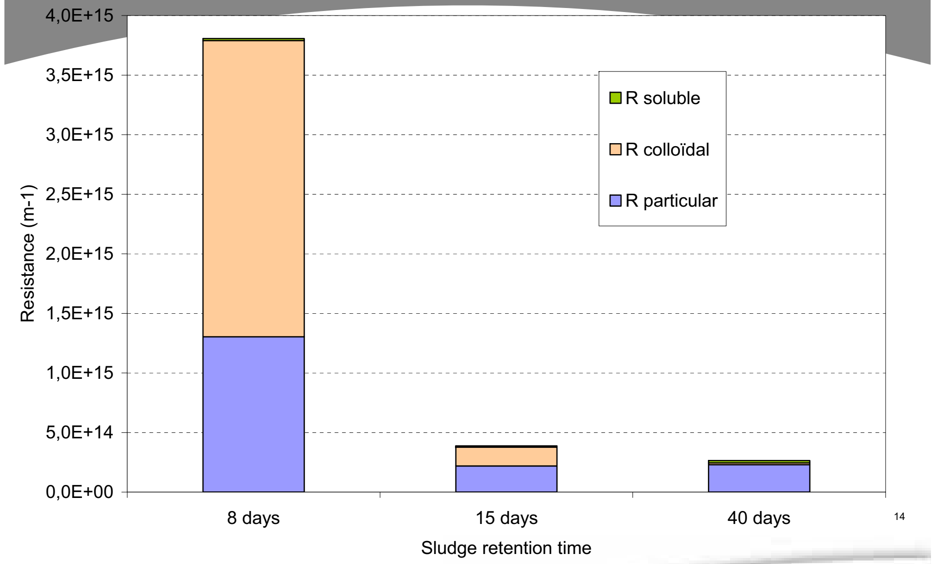
Rfiltrate = Rtotal –Rparticulate - Rcolloidal

↳ **Rcolloidal =** Rsupernatant - Rfiltrate

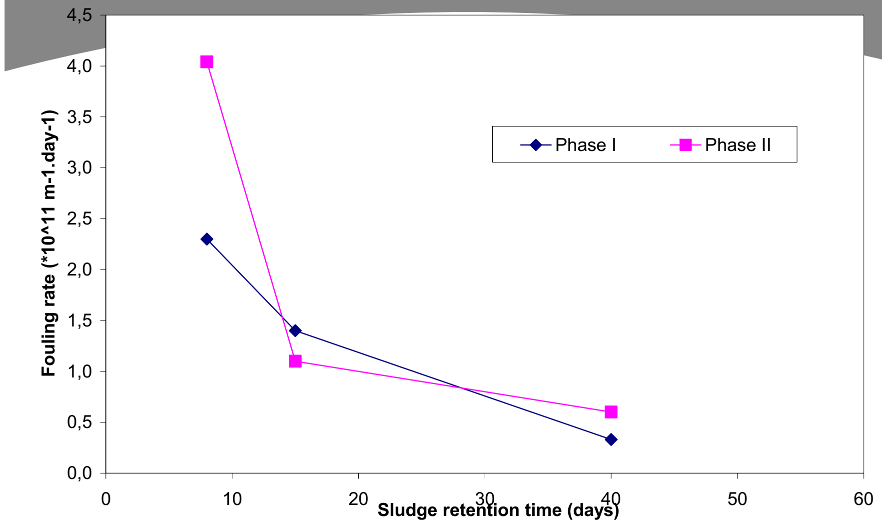
Membrane Resistance depending on the SRT

	8 days	15 days	40 days
R particulate	130.10^{13} m^{-1}	22.10^{13} m^{-1}	23.10^{13} m^{-1}
R colloidal	259.10^{13} m^{-1}	16.10^{13} m^{-1}	2.10^{13} m^{-1}
R soluble	2.10^{13}m^{-1}	1.10^{13} m^{-1}	2.10^{13} m^{-1}
Sludge filtrate Polysaccharides (mg/l)	# 33	# 14	# 5,2
Sludge filtrate Protein (+humics) (mg/l)	# 34	# 15	# 10

SRT influence on the sludge fouling potential



Fouling rate depending on the SRT



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summarize

- Filtrability sludge depends on the polysaccharides concentration supernatant and application?
- The polysaccharides concentration depends on the sludge age
- Fouling components change with the sludge age
- The sludge age is more important than sludge concentration for laboratory system
- Fitrability is a good test to predict the fouling potential of the sludge
- **Pragmatic approch**
  - **Pilot tests are necessary to predict the fouling rate for each application**

Pilot operating conditions

	SRT 8 days		SRT 15 days		SRT 40 days	
	Phase I	*Phase II*	*Phase I*	*Phase II*	*Phase I*	*Phase II*
Volumetric loading rate [kgCOD/m3/d]	1.0	2.7	1.0	1.9	1.0	0.9
F/M ratio [kgCOD/kgMLSS/d]	0.3	0.3	0.2	0.2	0.1	0.1
Sludge concentration [g/L]	3.2	7.8	4.9	6.8	7.7	7.3
HRT [h]	12	4.5	12	6.0	12	12

Laboratory of Chemical & Environmental Engineering

Synthesis of 3 PhD thesis on fouling and role of proteins in MBRs

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Laboratoire d'ingénierie des procédés de l'environnement (L.I.P.E)

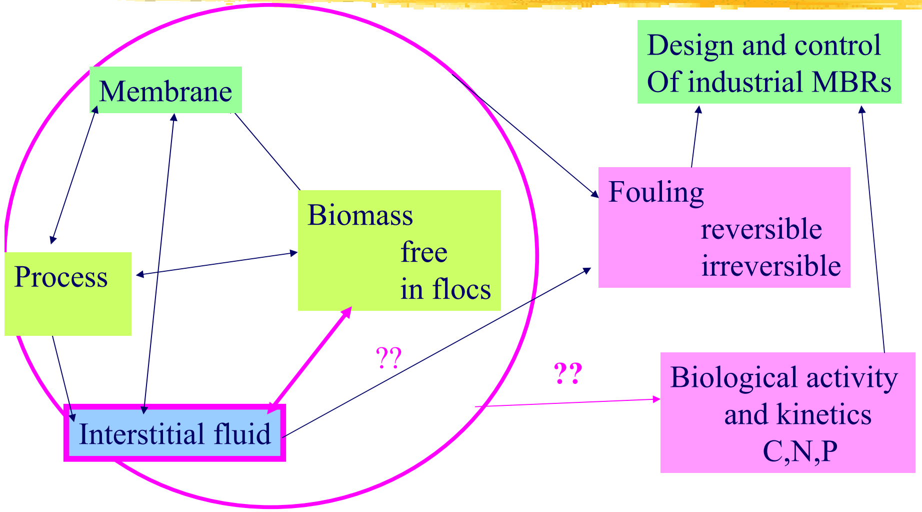
The 3 PhD Thesis

1. **Anthony MASSE**
   Bioréacteur à membranes immergées pour le traitement des eaux résiduaires urbaines : spécificités physico-chimiques du milieu biologique et colmatage
2. Maricarmen ESPINOSA

   Contribution à l'étude d'un Bioréacteur à membranes Immergées: Impact de la configuration du module et des conditions d'aération sur le colmatage particulaire et modélisation de l'activité biologique
3. Nicolas LESAGE

   Etude d'un procédé hybride adsorption/bioréacteur à membrane pour le traitement des effluents industriels'

Possible synergies



Membrane

Process

Biomass
free
in flocs

Interstitial fluid

??

Design and control
Of industrial MBRs

Fouling
reversible
irreversible

??

Biological activity
and kinetics
C,N,P

Fouling in submerged MBRs

2 SCALES
BUNDLE CLOGGING

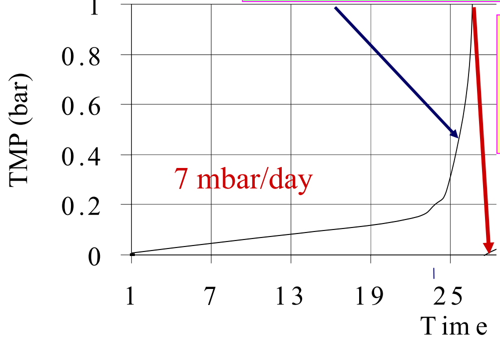
FOULING

Example of long-term filtration behavior

Fp = 5 L/H/m² - Without backwashes

Also observed by

(Cho and Fane, 2002; Ognier et al, 2001,…)



Simple cleaning procedure

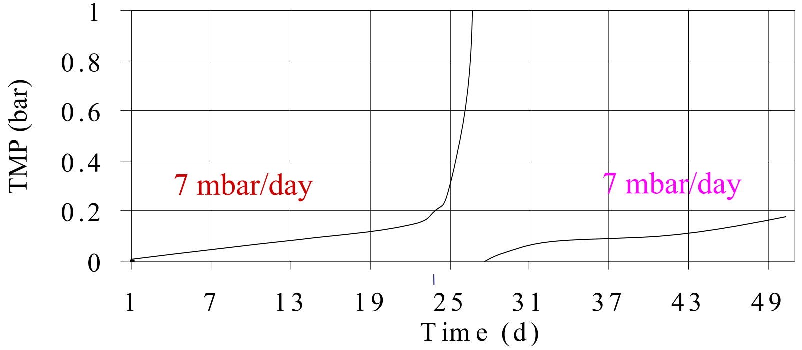
Rinsing

Backwash: 1.5 bar - 30 min,

Filtration: chlorine (1g/L) - 15 min

Long-term filtration behavior

Fp = 5 L/H/m² - Without backwashes



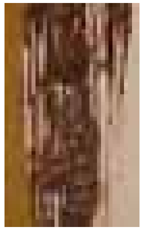
At a low permeate flux operation during 50 days:

- **without sequential backwash**
- **with a simple fouling prevention by a low air flow rate**

Problems ?

- ➔Can we prevent or limitate bundle clogging?
- ➔Is it reasonable to use conventional engineering data (biokinetics of activated sludges) to design MBR?
- ➔How to avoid long-term strong fouling ? What is it due to ?

Can we prevent or limit bundle clogging ?

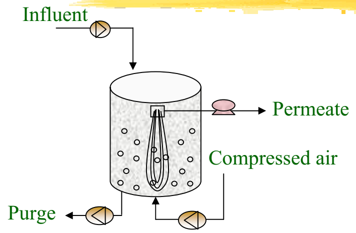


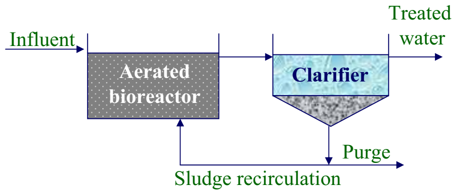
- ➔Bundle and fiber optimization
  - Fiber motion
  - Mechanical resistance
- ➔Aeration optimisation : compromise between removal efficiency and energy consumption
  - ➔Sequential aeration
  - ➔Separation of the two aeration functions
  - ➔Technical solutions for air channeling
- ➔Adapted de-concentration of the module –new systems configurations

No our topic of today ….

Is it reasonable to use CAS data to design a MBR?

A CAS and a MBR with the same conditions domestic wastewater

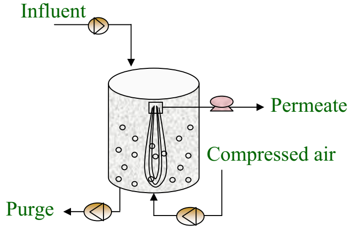




MBR CAS

	SRT CAS (d)	Stabilized MLSS (CAS) ($mg.L^{-1}$)	SRT MBR (d)	Stabilized MLSS (MBR) ($mg.L^{-1}$)
Period 1 (0 to 52 d)	9.2	1.6	9.8	1.9
Period 2 (120 to 217 d)	32.0	2.9	37.2	4.0
Period 3 (218 to 319 d)	14.3	2.1	110.3	7.2
Period 4 (320 to 420 d)	-	-	53.0	6.0

A CAS and a MBR with the same conditions domestic wastewater



MBR

Type (Polymem)	Hollow fibers
Material	Poly sulfone
Filtration area	0.23 m^2
Mean pore diameter	0.1 µm
Inner diameter	0.38 mm
Outer diameter	0.72 mm
Permeability (20°C)	225 $l.h^{-1}.m^{-2}.bar^{-1}$

Aeration conditions

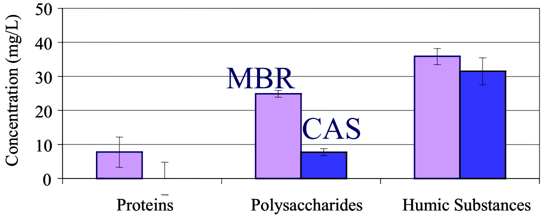
MBR	Sequential fine bubbles	DO=1-6 $mg.L^{-1}$ (1h30/1h30)
	Continuous coarse bubbles	$3.5.10^{-4}$ $m^3.s^{-1}.m^{-3}$ $2.8.10^{-5}$ $m^3.s^{-1}.m^{-2}$
CAS	Sequential fine bubbles	DO=1-6 $mg.L^{-1}$ (1h30/1h30)

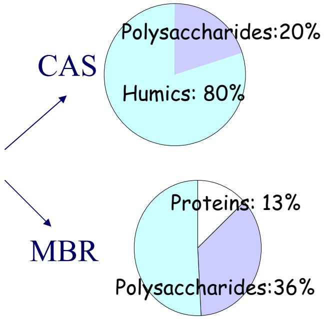
Influence of the membrane on sludge properties

- Composition of the supernatant ?
- Floc properties?
- Fouling ability of the biomass ?
- Biological activity of biomass and supernatant ?

Main differences in the supernatant ?

Supernatant SRT= 10 days



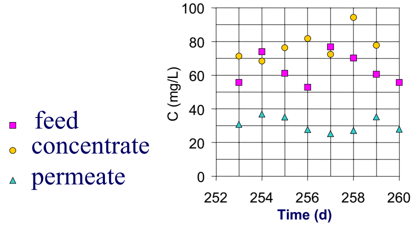


Strong modifications of Polysaccharides and Proteins contents in the supernatant

Massé et al, 2003

Retention of SMP in the MBR

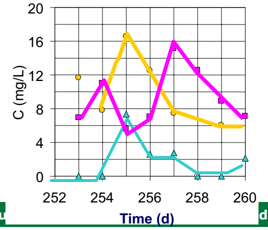
Total SMP: R=46-71%



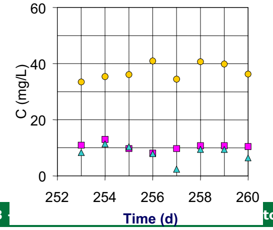
Accumulation of SMP after each starting period

No retention of humics

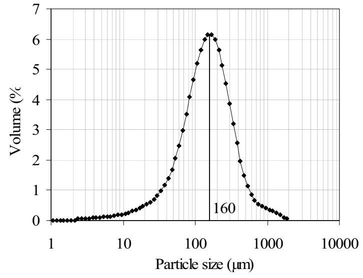
Proteins : R= 55-100



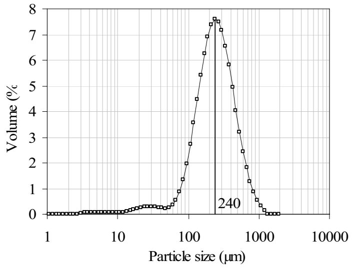
Polysaccharides: R=67-83%



Are the biological flocs identical ?

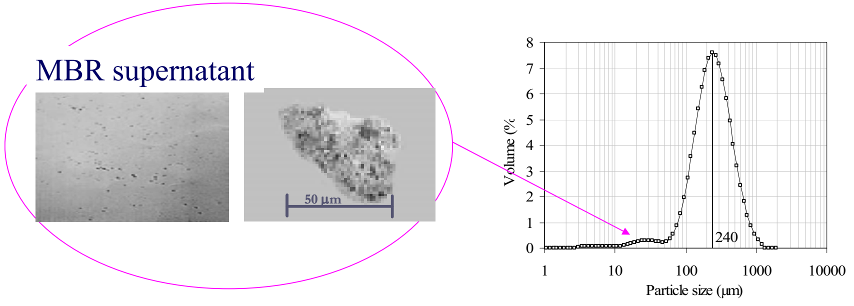


CAS



Submerged MBR

Are the biological flocs identical ?



Submerged MBR

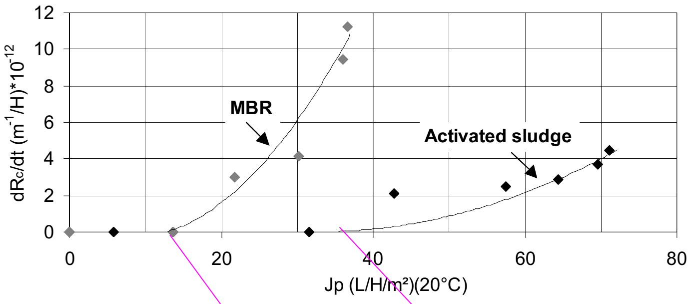
In the MBR : 2 populations:
- some free bacteria and small flocs
- higher diameter flocs

Could contribute to particulate fouling

Fouling ability of sludge in a submerged MBR and in a CAS

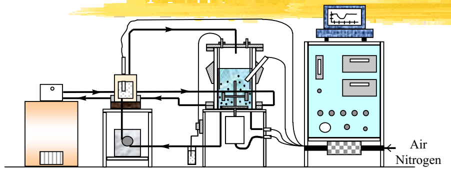
(SRT=10 days, MLSS= 2 g/L)

Massé et al, 2004

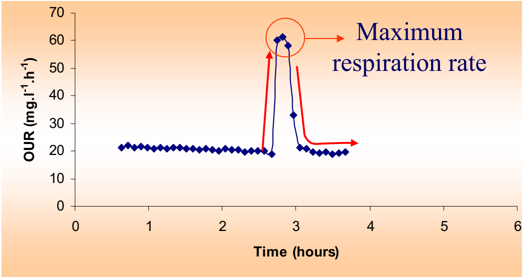


Much higher fouling ability in the MBR for the same MLSS:
- the membrane modifies the biological fluid

Determination of biological activity



Samples of activated sludge
- membrane bioreactor
- activated sludge system



Biokinetics: biological activities of sludge and interstitial fluid

Biological activities: Oxygen uptake rate determined by respirometry

SYSTEM	Autotrophic ($mgO_2.l^{-1}.h^{-1}$)	Autotrophic ($mgO_2.l^{-1}.h^{-1}$)	Heterotrophic ($mgO_2.l^{-1}.h^{-1}$)	Heterotrophic ($mgO_2.l^{-1}.h^{-1}$)
	Supernatant	**Sludge**	**Supernatant**	**Sludge**
MBR	**1.12**	38	**0.82**	28
CAS	< 0.1	28	< 0.1	16

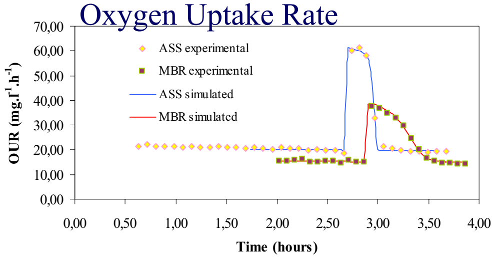
Espinosa et al, 2004

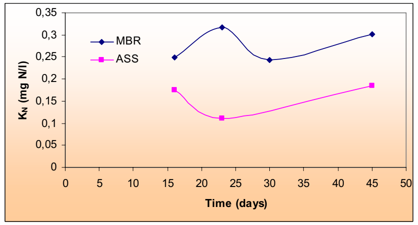
Different biological kinetics
Most activity in sludge

Biological activity ?

$$r_N = \left(-\frac{1}{Y_A} - i_{XB} \right) . \mu_{max.A} . X_{BA} . \frac{S_{NH}}{S_{NH} + K_N}$$

Oxygen Uptake Rate



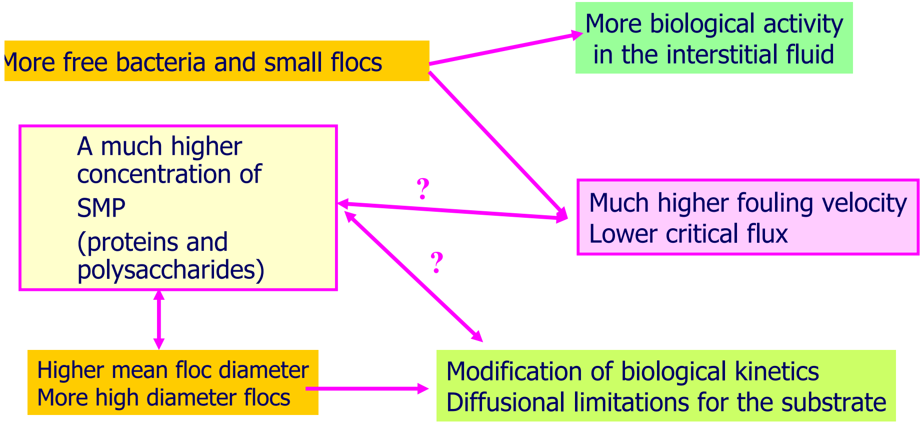


nitrification kinetics after
NH_4Cl addition for MBR and CAS.

Apparent affinity constant Kn
$Kn_{AS} << Kn_{MBR}$

Diffusional limitations in flocs

new data have to be considered for MBRs



More free bacteria and small flocs

More biological activity in the interstitial fluid

A much higher concentration of SMP (proteins and polysaccharides)

?

?

Much higher fouling velocity
Lower critical flux

Higher mean floc diameter
More high diameter flocs

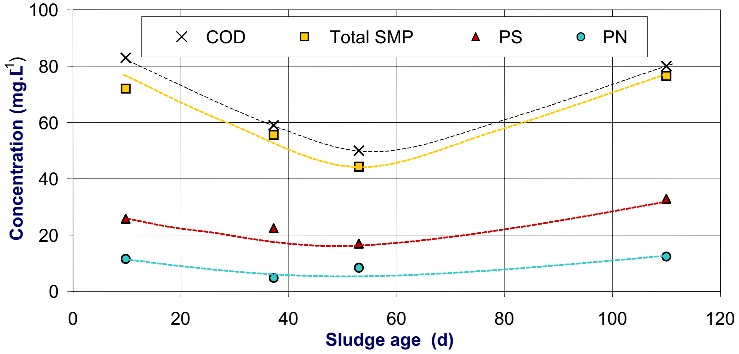
Modification of biological kinetics
Diffusional limitations for the substrate

Influence of sludge age

SRT = 32-160 days

Influence of sludge age on supernatant properties

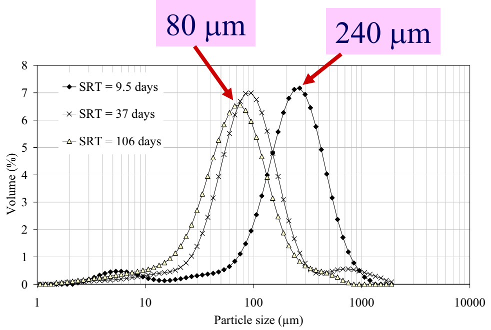
Supernatant



There is an optimal SRT in terms of SMP: > 50 days

Accumulation due to membrane ⟺ Biodegradation

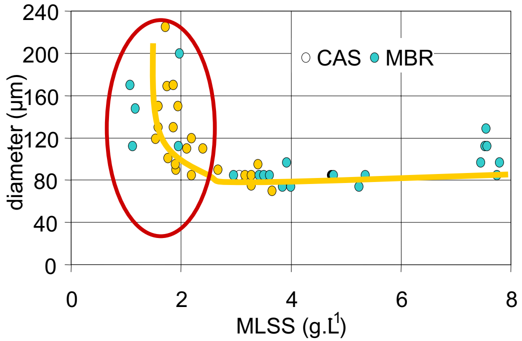
Influence of SRT on floc properties: floc size



Increasing the sludge age in the MBR:

- Decreases the mean floc size diameter
- Modifies the population of small particles

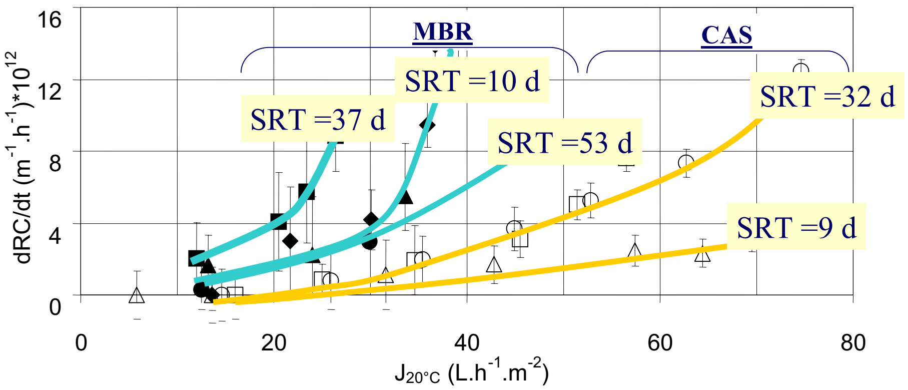
Influence of SRT on floc properties: floc size



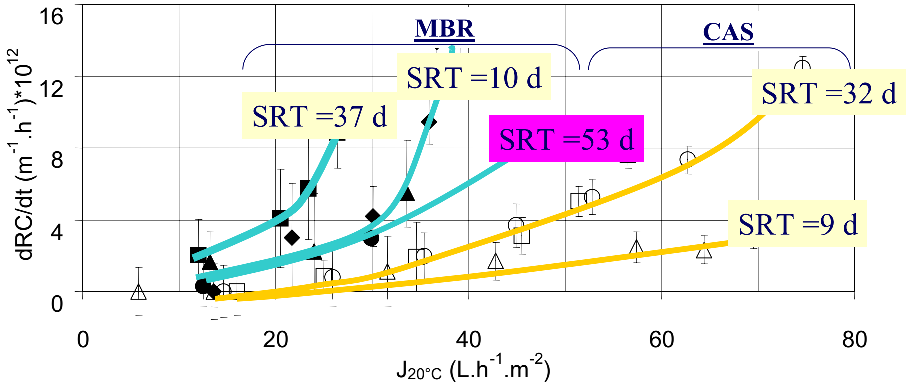
At low SRT:
a large range of floc diameters

At high SRTs:
stabilization of floc diameter
No difference CAS/MBR

Fouling velocities of sludges sampled from the 2 systems

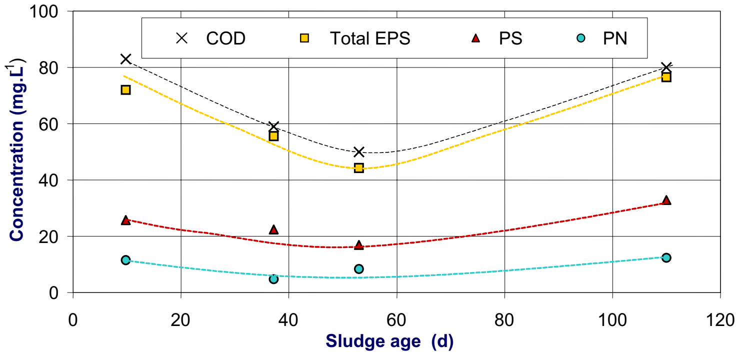


In the CAS, fouling velocity increases with SRT
In the MBR, fouling velocity increases and then decreases at higher SRT



Link between fouling ability and supernatant composition

Supernatant

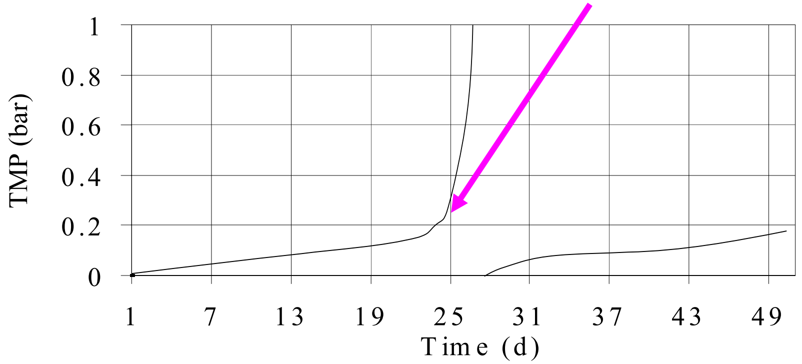


There is an optimal SRT in terms of EPS : > 50 days

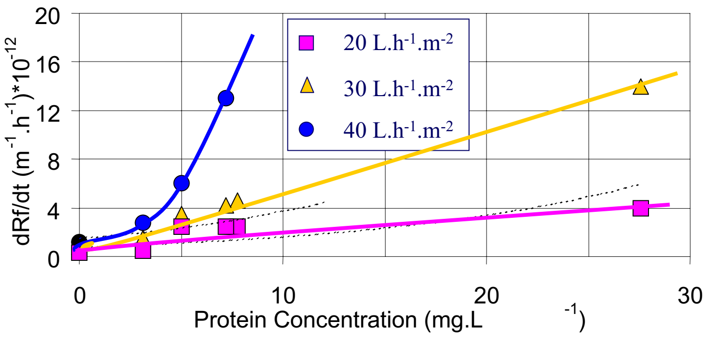
Can explain why fouling velocities for MBR are lower at SRTs close to 50 days

How to explain long-term fouling?

How to avoid it?

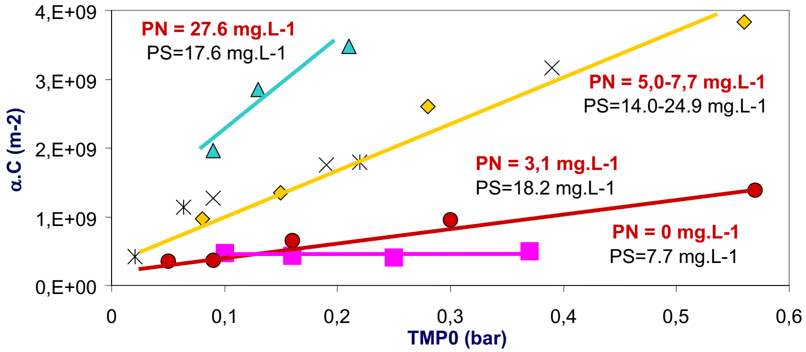


Influence of proteins on fouling velocities



Fouling velocity increases with permeate flux
and with protein concentration in the supernatant

Influence of proteins and PS on cake properties

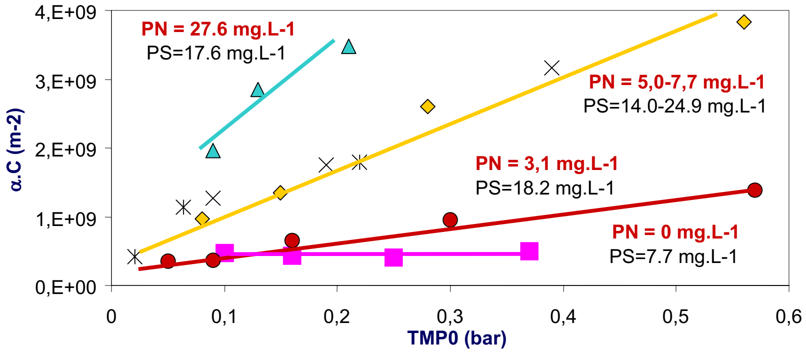


Without proteins : no variation of α.C with TMP

For PN > 0 : α.C increases linearly with TMP

When PN ⇧ α.C increases more rapidly

Influence of proteins and PS on cake properties

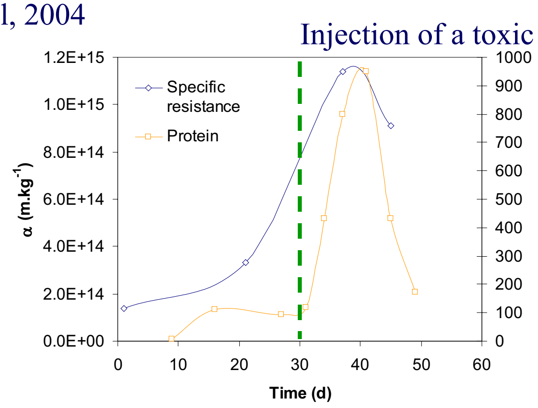


Proteins are retained by the membrane as colloïds or as a gel

Proteins contribute to cake structuration and affect
C : deposited mass
And/or α : compressibility of the cake

Dynamics analysis

Lesage et al, 2004



Lesage et al, 2005

Confirms that fouling dynamics is related to protein concentration

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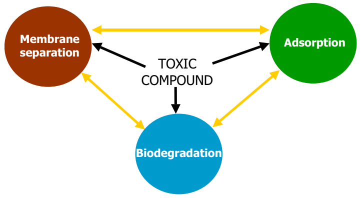
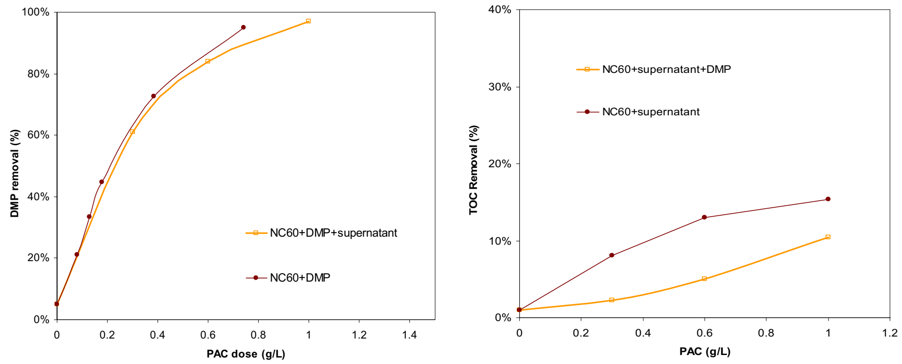
Other possible MBR configurations

- Hybrid Adsorption/Bioreaction/membrane systems for the removal of toxics

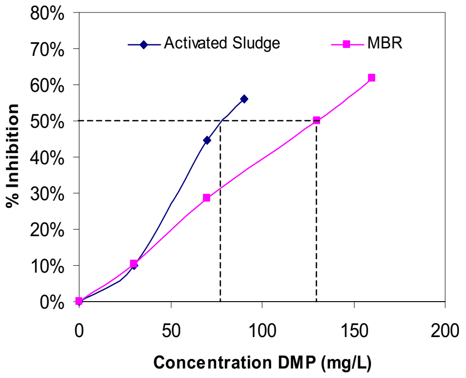


Effect of the hybrid MBR on water quality



Enhancement of TOC removal
of DMP removal

An other interest of MBRs = a better resistance to toxics

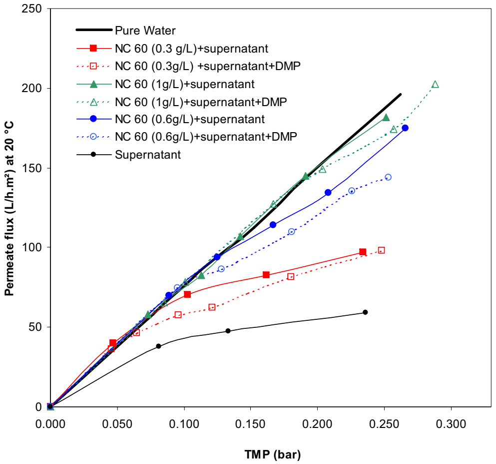


Lesage et al, 2004

- ✓ EC_{50} :concentration in toxic inducing a 50% reduction in biological activity

sludge	Activated	MBR
EC_{50} (mg $DMP.L^{-1}$)	78 ± 10	130 ±10

Effect of the PAC adjunction on short-term fouling



Lesage et al, WFC, 2004

A positive effect for concentrations lower than 4 g/L

Biomass adaptability to the toxic and long-term fouling

Hybrid MBR

MBR

Lesage et al, 2005

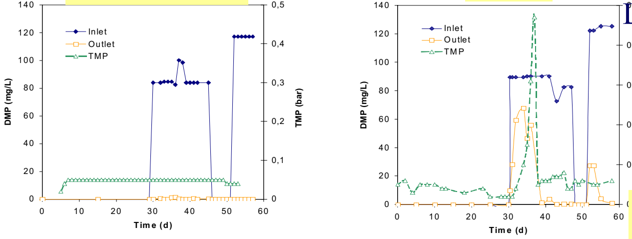


Figure 2 : Profile of DMP (inlet and outlet) and TMP, in a HMBR (a) and MBR (b)

The hybrid MBR = a way to avoid long-term fouling ?

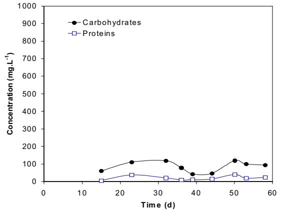


Figure 3 : Evolution of EPS concentration in H-MBR supernatant

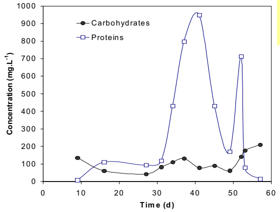
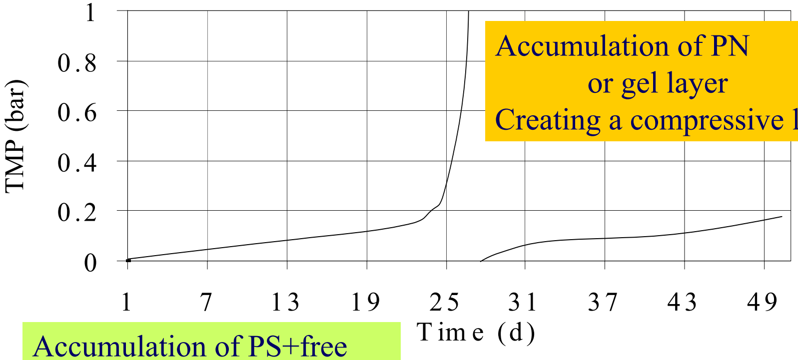


Figure 4 : Evolution of EPS concentration in MBR supernatant



Accumulation of PN
or gel layer
Creating a compressive layer

Accumulation of PS+free cells + colloids (inside pores and on surface)

Conclusion/1

- Comparison of CAS and MBR for the same and low MLSS concentration
- Strong modifications of
  - the biological fluid (SMP + particle distribution)
  - Fouling ability
  - Biological activity
- Existence of an optimum SRT for which SMP accumulation and fouling are minimum

DUE TO MEMBRANE RETENTION

New kinetic and fouling data have to be considered for process design

Conclusion/2

- ➔ Long-term fouling can be explained
  - By a strong influence of proteins in supernatant
  - A cake sensitivity to pressure : compressibility effects
- ➔ Accumulation of proteins and long-term fouling can be due to
  - Membrane (+biofilm) retention
  - Cell release in case of toxic activity or stress
- ➔ Interests of a hybrid CAP-MBR reactor
  - « protection of cells »from toxics : no more protein release and no more long-term fouling
  - Better treatment efficiency

Key questions

- Which is the role of small particles and colloids in fouling?
- Who are the proteins involved in long term fouling?
  - Colloids/soluble?
  - Which kind of proteins?
- Can we avoid long term fouling if bacteria are submitted to no-stress ?
- How to develop a process which is totally « cocooning » bacteria ?

Thanks to

Dr Mathieu Spérandio
Dr Anthony Massé
Dr Nicolas Lesage
Dr Maricarmen Espinosa

POLYMEM (MEMBRANE MANUFACTURER)

MIDI PYRENEES COUNCIL
IFP
ADEME

Can we control the fouling with flux enhancing chemicals?

Vera Iversen, Loic Bonnet, Anja Drews, Boris Lesjean,
Jana Schaller, Matthias Kraume

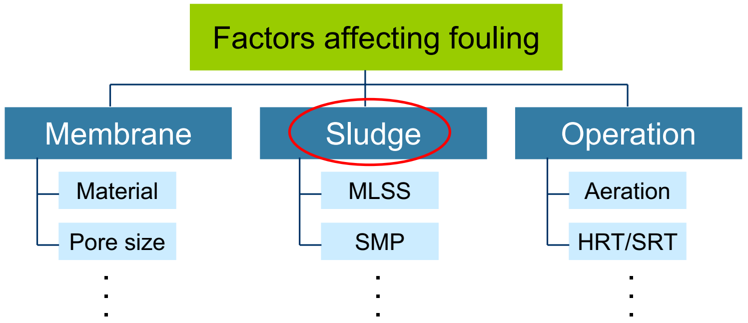
KOMPETENZZENTRUM Wasser Berlin

Agenda

- Background & Aim
    - Development of a fouling sensor
- Materials & Methods
    - Jar tests
    - Cross flow test cell
- Results
    - SMP reduction
    - Fouling mechanisms
- Summary & Conclusions

Fouling in MBRs

- Reduces productivity
- Shortens membrane lifetime
- Increases operation costs
- More than 30% of MBR-publications deal with fouling (Yang et al. 2006)

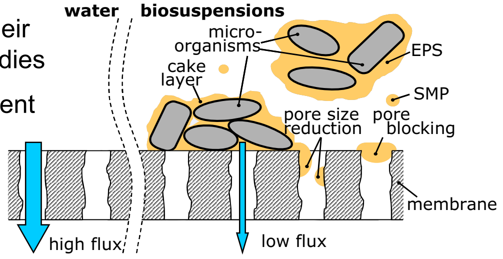


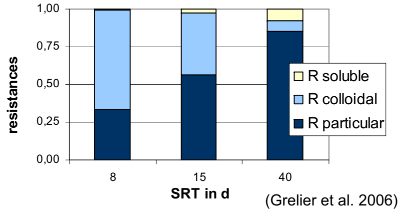
Factors affecting fouling

- Membrane
    - Material
    - Pore size
    - ⋮
- Sludge
    - MLSS
    - SMP
    - ⋮
- Operation
    - Aeration
    - HRT/SRT
    - ⋮

What causes fouling?

- Evaluation of foulants and their impact differs in different studies
- Different results due to different operation conditions

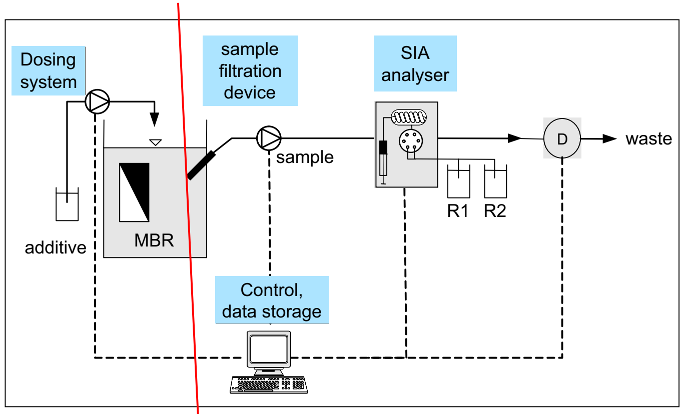




(Grelier et al. 2006)

Recent studies stress the importance of soluble and colloidal material like SMP

Fouling control system



Chemical Engineering | Water Quality Control

SMP elimination in sludge

How can SMP be eliminated?

Flocculation, coagulation, adsorption

Up to now…

no systematic comparison between different chemicals

no adapted dosing

little information on th

little information on S

little information on b

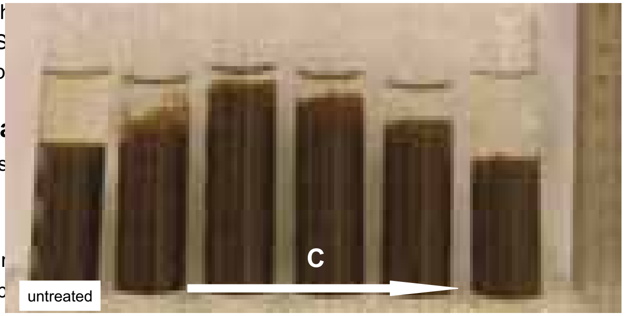
What substances a

Metal salts, enzymes

Aim of this work

screening for a maxi

preselection for the p

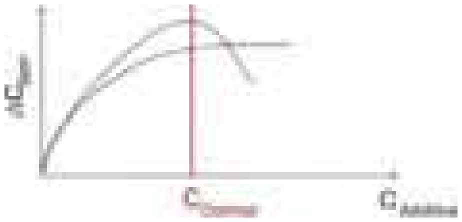


Materials & Methods

Jar tests

- SMP-Elimination with different additive concentrations

➡Optimal concentration



Filtration test cell

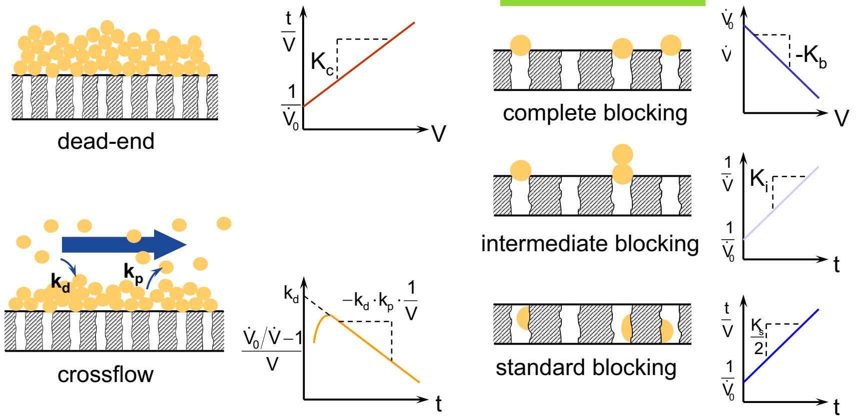
- Fouling tests with real sludge and optimal additive concentration
- Residual tests with water and 5% optimal additive concentration

Analysis of filtration mechanism

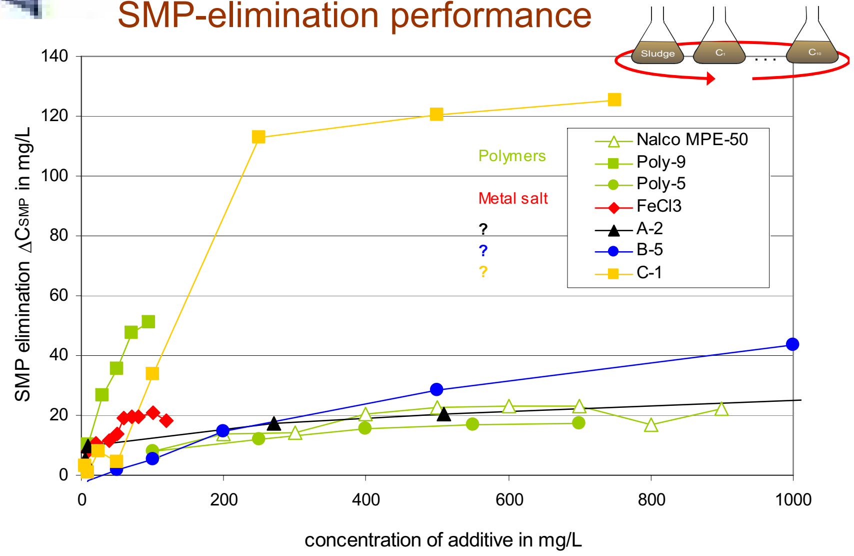
Models for cake filtration

Models for pore blocking

(Hermia et al. 1982)



SMP-elimination performance



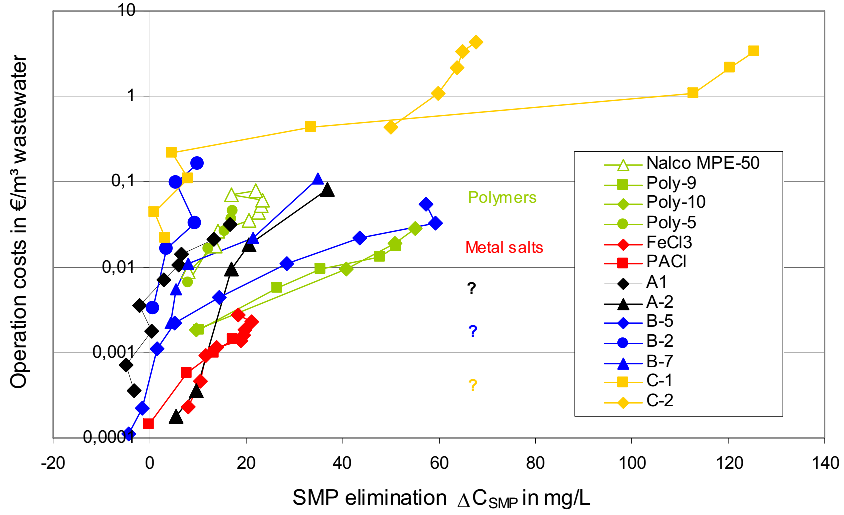
Preliminary economical analysis

Assumptions

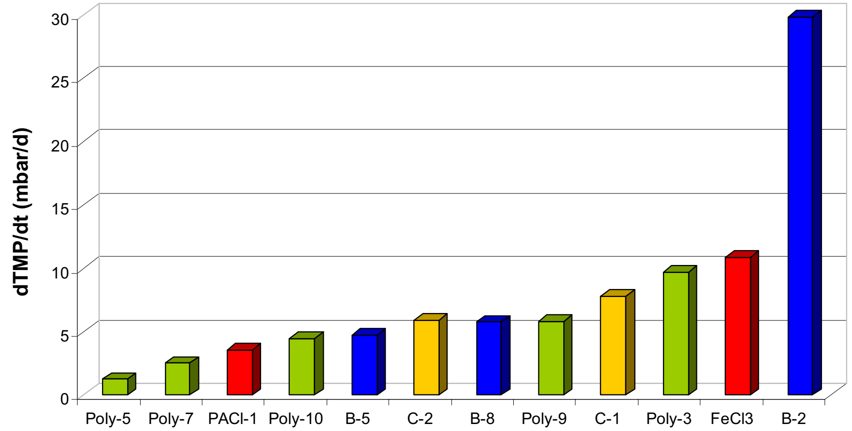
- Plant for 10 000 EW = 1500 m³/d
- SRT = 25 d
- HRT = 13 h
- C_{SMP} =100mg/L
- Sludge withdrawal was considered

Prices according to producers

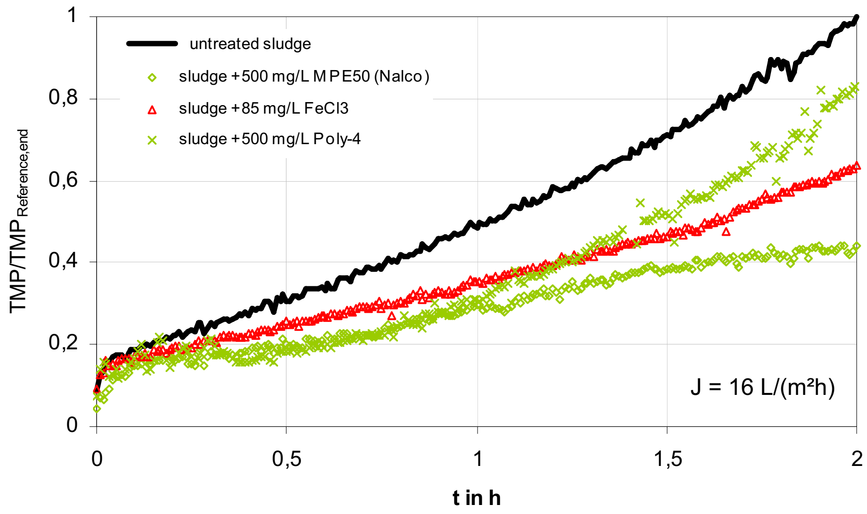
Preliminary economical analysis



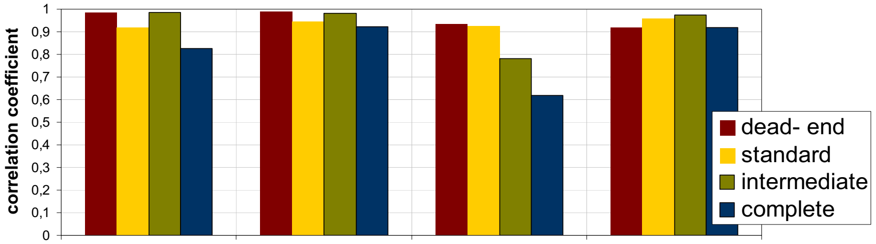
Residual tests

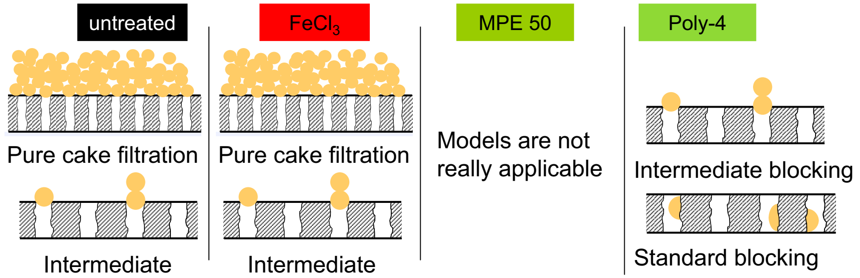


Influence of additives on fouling



Analysis of filtration mechanisms





untreated

Pure cake filtration

Intermediate

$FeCl_3$

Pure cake filtration

Intermediate

MPE 50

Models are not really applicable

Poly-4

Intermediate blocking

Standard blocking

Summary and outlook

- Additives are able to bind SMP
- Group C is most reactive but costly
- Additives reduce fouling rate and change fouling mechanisms
- Causes for this improvement (floc size, SMP, viscosity, porosity…) are not yet totally understood

To be done…

- Tests for biotoxicity
- Further tests with sludge in the cross flow test cell

Large scale tests in a 1.5 m³ reactor with selected additives

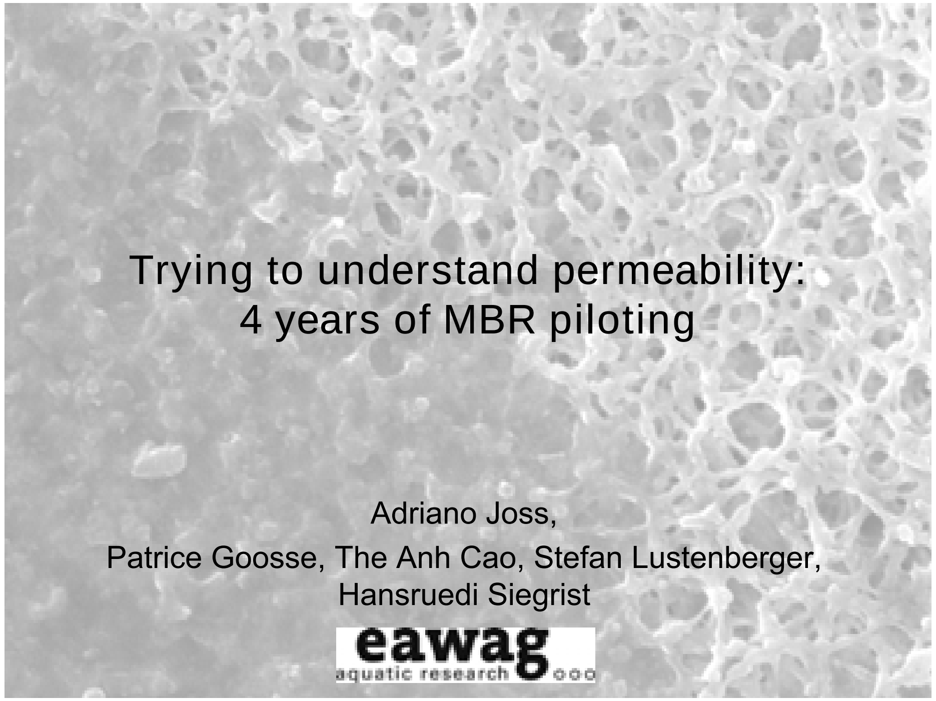
---

Acknowledgement

AMEDEUS is a research project supported
by the European Commission
under the Sixth Framework Programme
(Priority “Global Change and Ecosystems”)

Contract No. 018328 - AMEDEUS
Duration: 01/10/05 - 30/09/08
AMEDEUS is part of the MBR-NETWORK Cluster

More info: www.mbr-network.eu



Trying to understand permeability: 4 years of MBR piloting

Adriano Joss,
Patrice Goosse, The Anh Cao, Stefan Lustenberger,
Hansruedi Siegrist

WWTP Kloten/Opfikon: 55‘000 PE

Wastewater:
50% households +
50% airport Zürich

Grid

Primary settler

MBR-Pilot
100 PE

Municipal wastewater

Flow proportional to sewer

MBR for 100 PE

18 m^3 max reactor volume

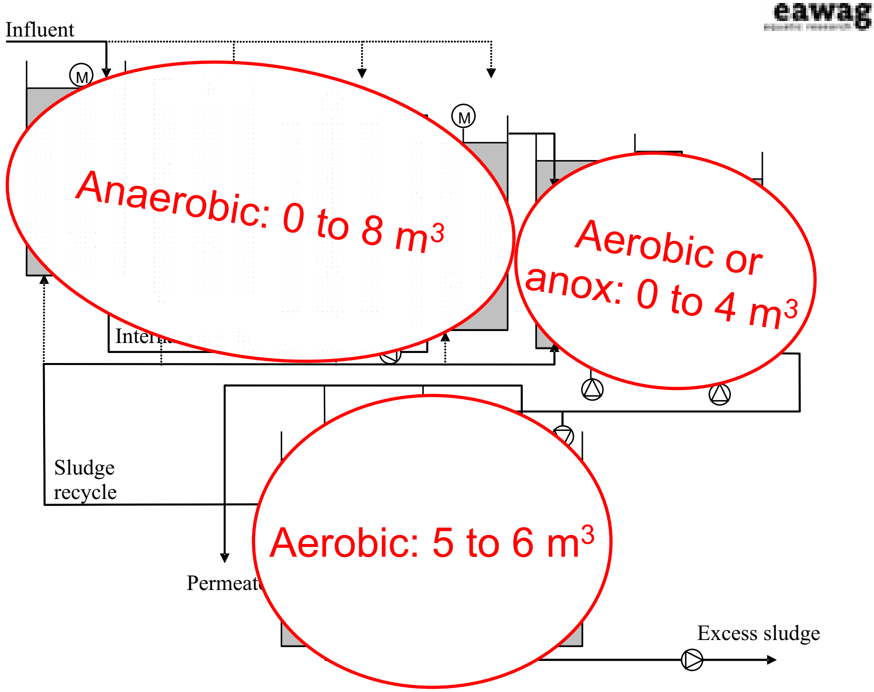
3 modules:

Kubota:	1 m^3 h^{-1}
Mitsubishi:	1 m^3 h^{-1}
Zenon:	1 m^3 h^{-1}

Operation

June 2001 to

September 2005

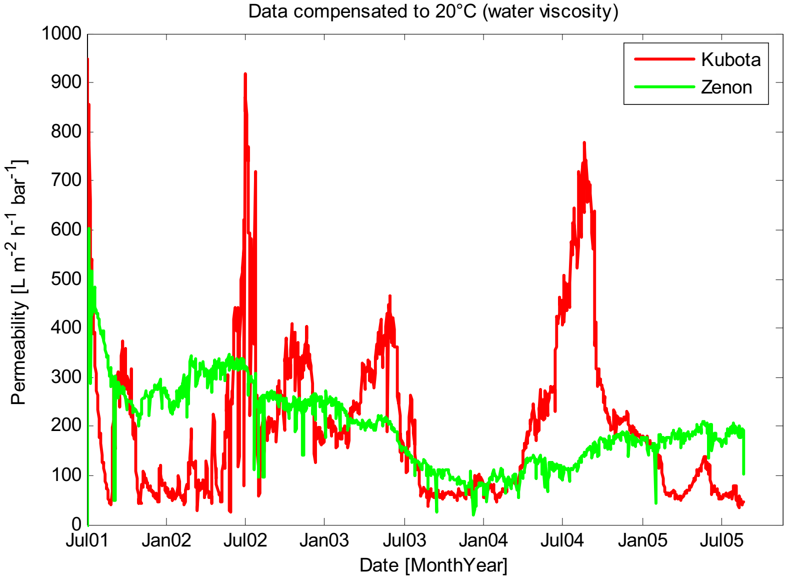


Anaerobic: 0 to 8 m^3

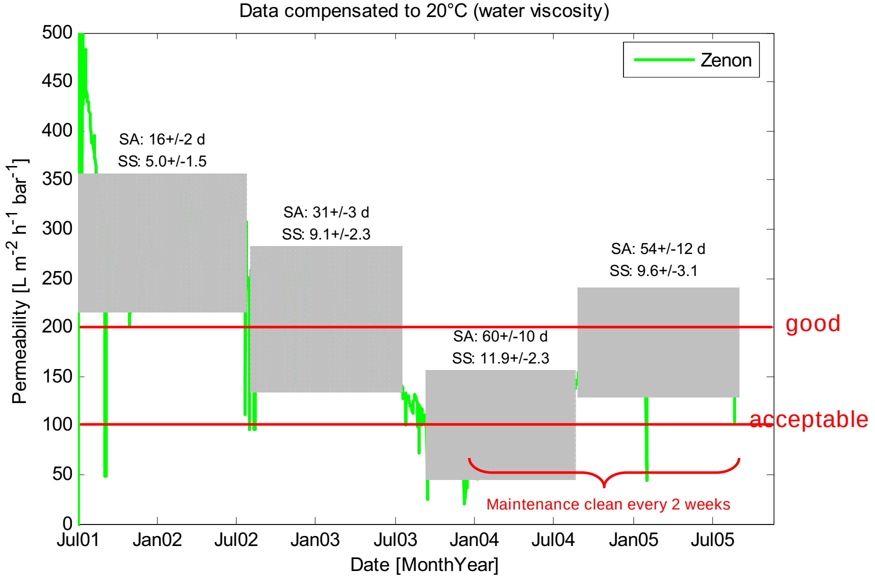
Aerobic or anox: 0 to 4 m^3

Aerobic: 5 to 6 m^3

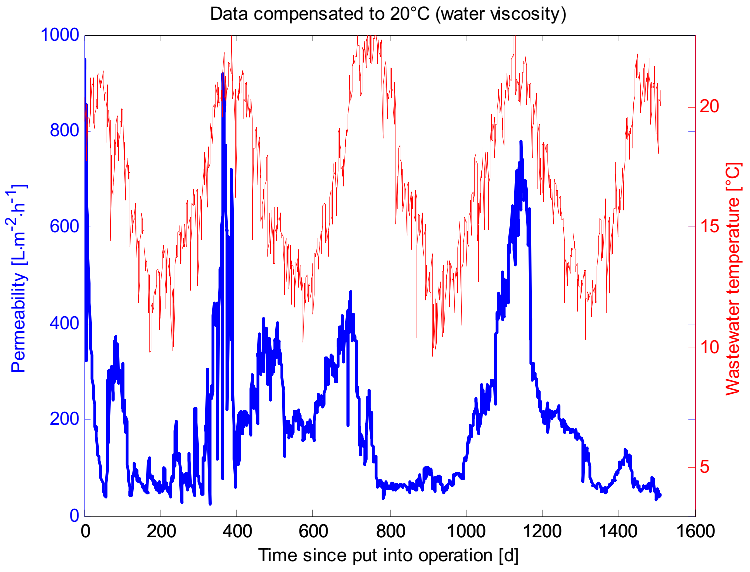
Permeability during 4 years



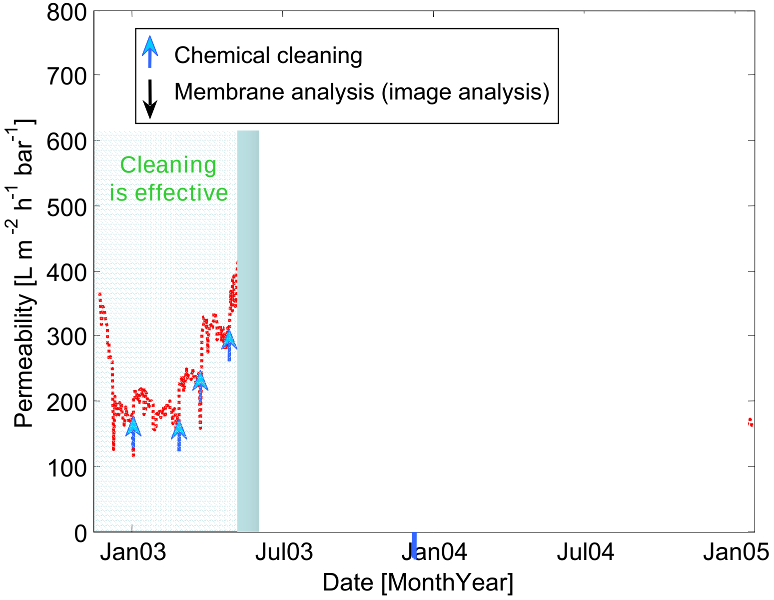
Permeability of Zenon



Kubota: seasonal variation



What influences the permeability of Kubota?



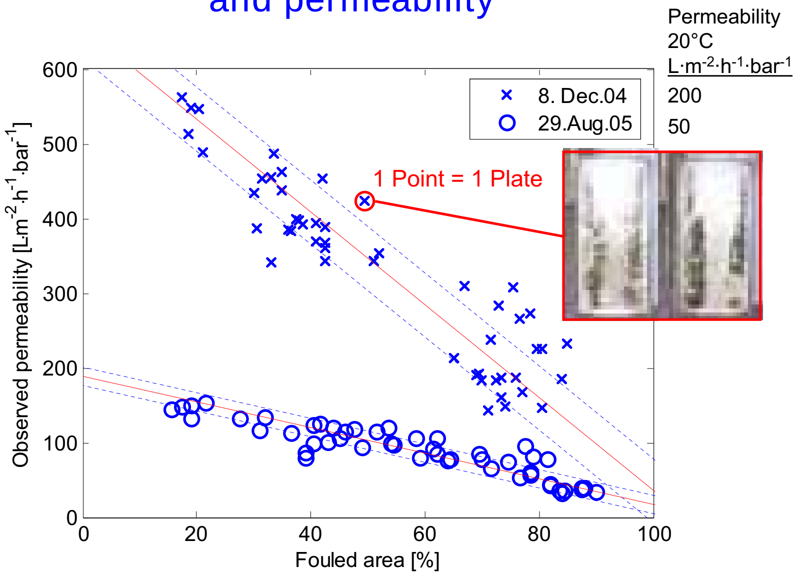
Optically visible fouling

<25% 25%< to <65% >65%

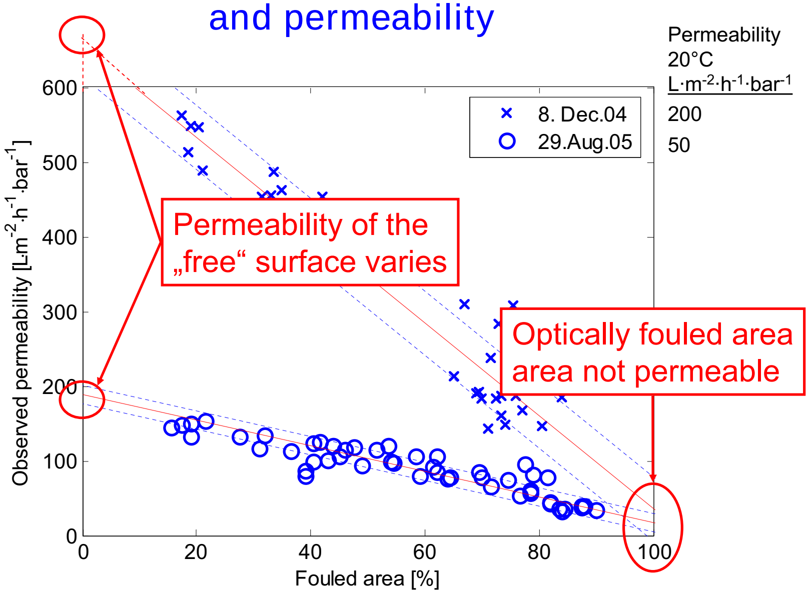
21. June 04: 1/3 membranes 1/3 membranes 1/3 membranes

21. Juni 04: 3 years of operation
21. Juni 04: Permeability 400 L m^{-2} h^{-1} bar^{-1}

Correlation of observable fouling and permeability



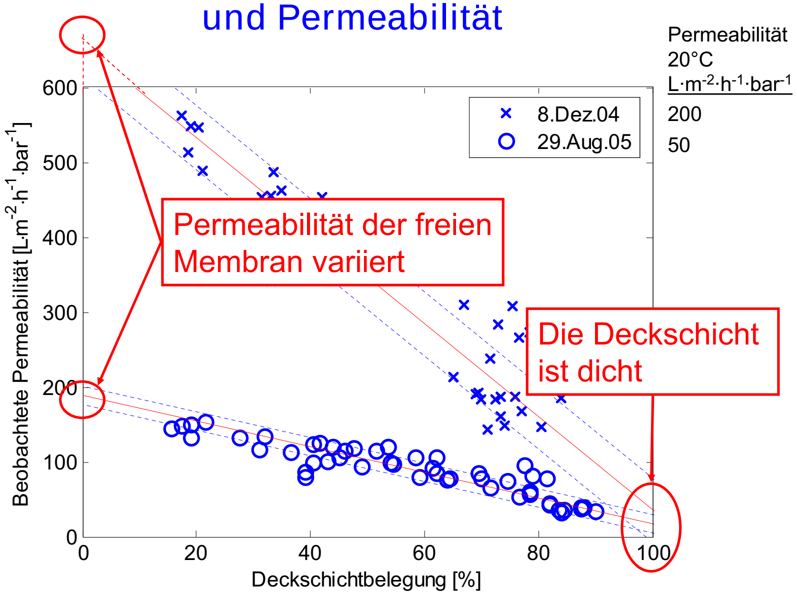
Correlation of observable fouling and permeability



Permeability of the „free“ surface varies

Optically fouled area area not permeable

Korrelation von Deckschicht und Permeabilität



Permeabilität der freien Membran variiert

Die Deckschicht ist dicht

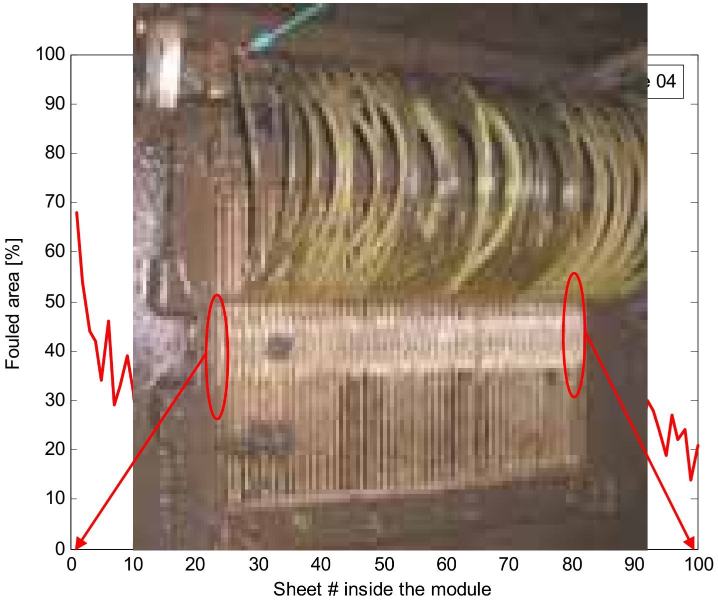
Conclusion

- Visible fouling has negligible permeability
- Seasonally variable fouling of Kubota originates in the non visibly fouled area
  - Effect not seen on Zenon membrane:
    - Pore size difference: 0.4 vs. 0.04 µm? Specific sludge particle size?
    - Regular backwashing of the membrane: Plate vs. hollow fibre?
- Permeability in Zenon is sensitive on
  - sludge concentration
  - regular maintenance clean

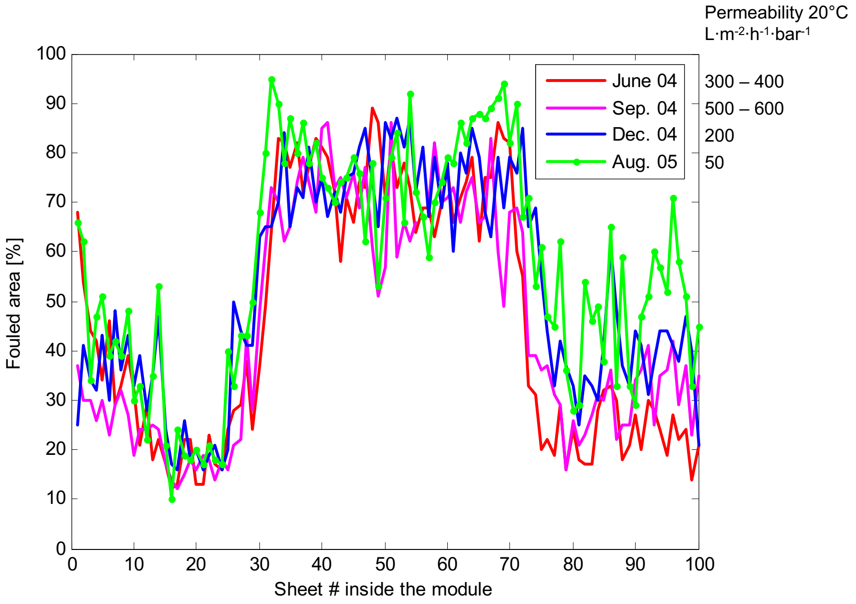
Thank you

FOEN
Kantons: AG, BE, BL, LU, SG SH, SZ, TG, TI, ZH
WWTP Kloten/Opfikon

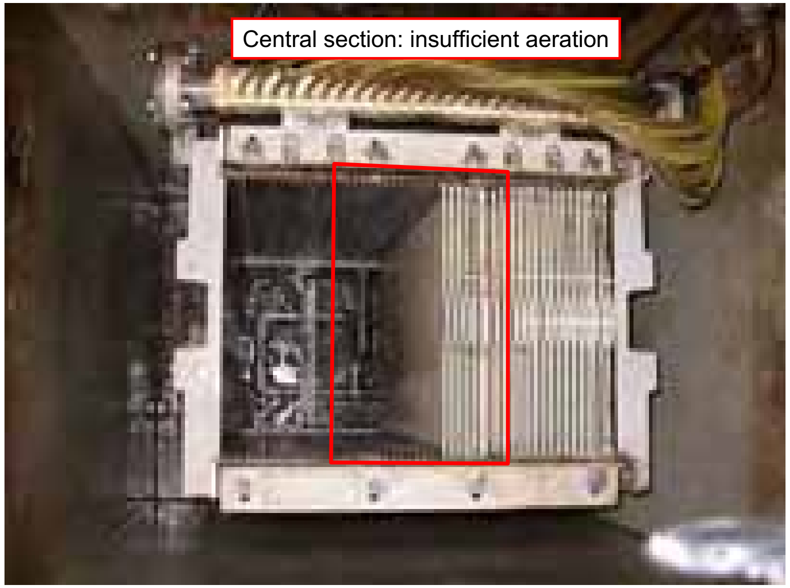
Picture analysis of all 100 membrane surfaces



Picture analysis of all 100 membrane surfaces

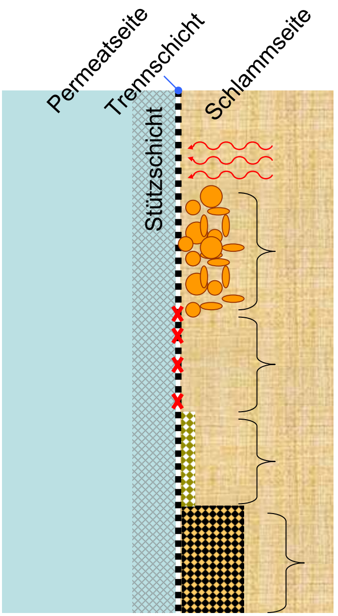


Old aeration unit



New aeration unit: improved air sparging

Permeabilität vs. einzelne Durchflusswiderstände



Flusswiderstand:	Gegenmassnahme:
Membran	Membrantyp (Porosität)
Schlamm Filtrationswiderstand	Reaktorkonfiguration? Flockungshilfsmittel?
Reversible Deckschicht	Permeat Rückspülung
Porenverblockung	Chemische Rückspülung
Deckschicht nicht sichtbar	Chemische Reinigung
Deckschicht sichtbar (Bilderkennung)	Grobblasige Belüftung Mechanische Reinigung

---

Klarwasser Permeabilität

Mechanische Reinigung der Membran

Kosten: 0.02 €$\cdot$m$^{-3}_{\text{Abwasser}}$
bei jährlicher Reinigung

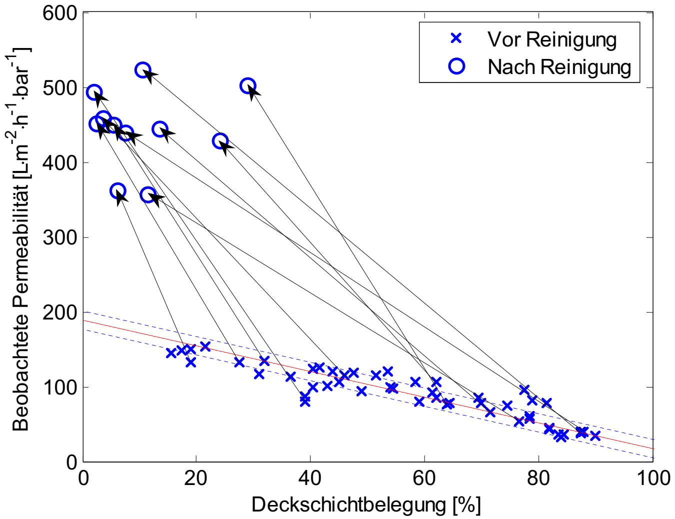
1 Platte = 0.8 m^2

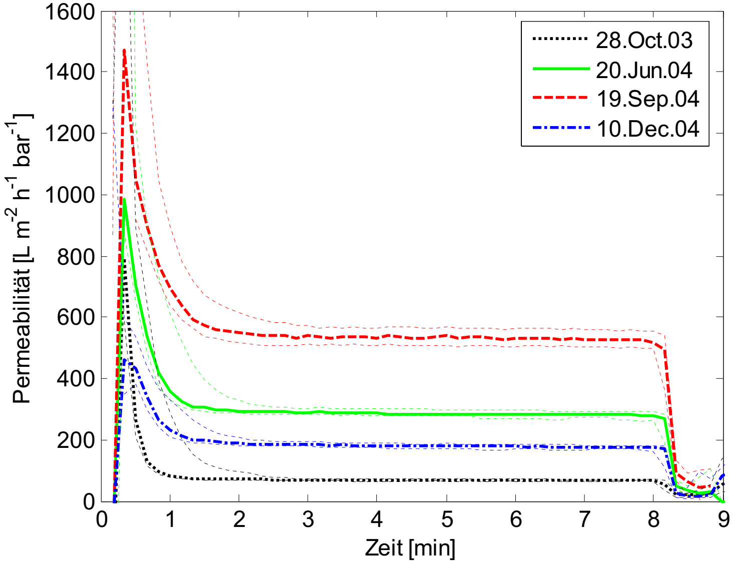
5 min/Platte
(inkl. Aus-/Einbau)

Arbeiter: 25 €$\cdot$h^{-1}

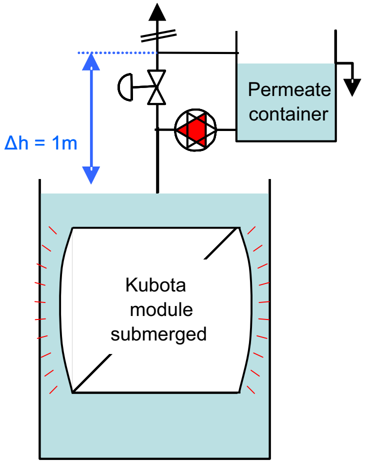
Permeatfluss im Mittel:
15 L$\cdot$m$^{-2}\cdot$h^{-1}

Mechanische Reinigung der Membran



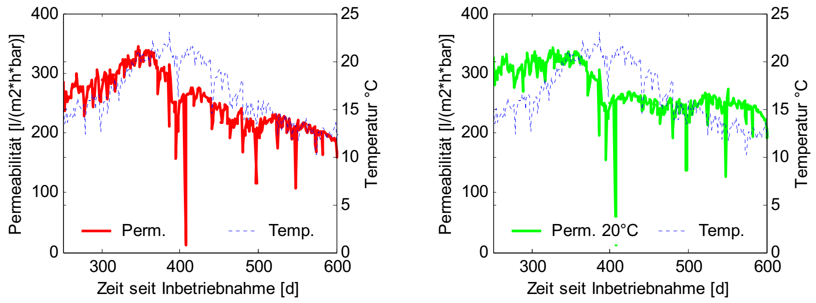


Backwashing Kubota



Temperature compensation

$$\xi_{20^\circ C} = \frac{\eta_T}{\eta_{20^\circ C}} \cdot \frac{Q}{A \cdot \Delta p} = e^{0.026 \cdot (20-T)} \cdot \frac{Q}{A \cdot \Delta p}$$


Without temperature compensation

With temeperature compensation

Permeability of a Zenon ZW500-A module over one year

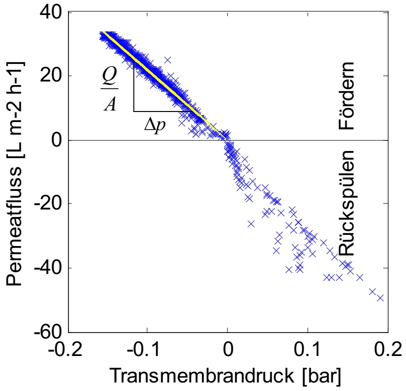
Die Permeabilität

Hagen-Poiseuille

$$\xi = \frac{Q}{A \cdot \Delta p} = \frac{d^2 \cdot \varepsilon}{32 \cdot \eta \cdot l}$$

ξ Permeabilität [$L \cdot m^{-2} \cdot h^{-1} \cdot bar^{-1}$]
Q Permeatfluss [$L \cdot h^{-1}$]
A Membranfläche [m^2]
Δp Transmembrandruck [bar]

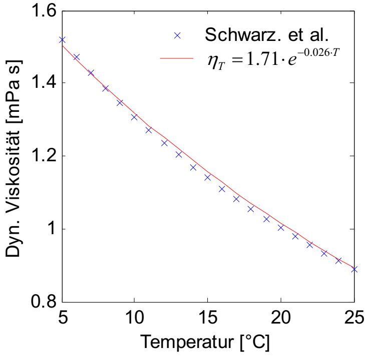
d Rohr- bzw. Porendurchmesser [m]
ε Porosität der Membran;
$\varepsilon = V_{Poren}/V_{Membran}$ [-]
η dynamische Viskosität [Pa·s]
l Porenlänge [m]



Temperaturabhängigkeit

Hagen-Poiseuille

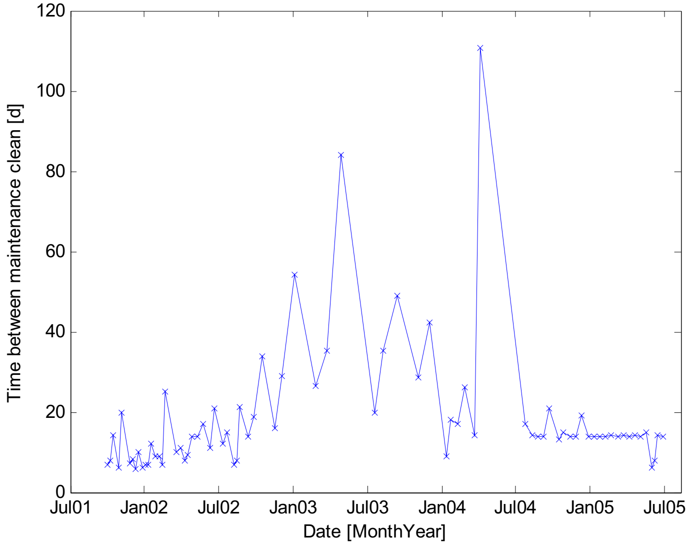
$$\xi = \frac{Q}{A \cdot \Delta p} = \frac{d^2 \cdot \varepsilon}{32 \cdot \eta \cdot l}$$

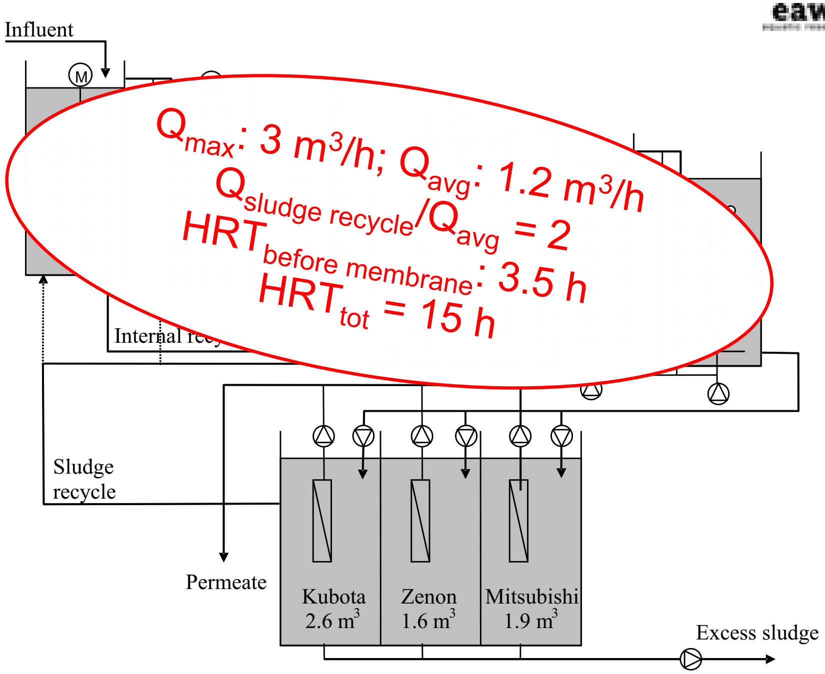


ξ Permeabilität [$L \cdot m^{-2} \cdot h^{-1} \cdot bar^{-1}$]
Q Permeatfluss [$L \cdot h^{-1}$]
A Membranfläche [m^2]
Δp Transmembrandruck [bar]

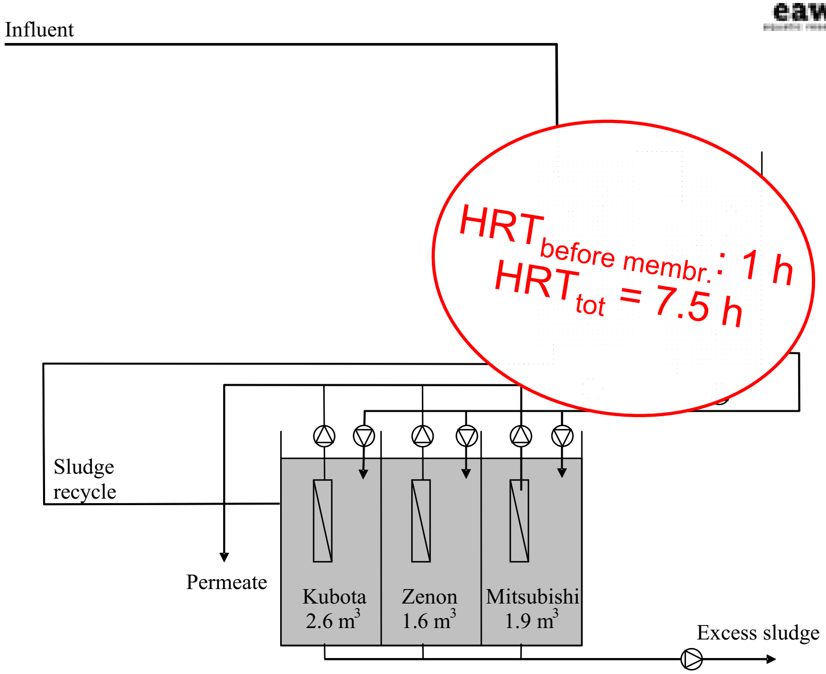
d Rohr- bzw. Porendurchmesser [m]	*Ausdehnung von Polymere*	*$5 \cdot 10^{-5}$ - $2 \cdot 10^{-4}$* K^{-1}
ε Porosität der Membran;	-	-
$\varepsilon = V_{Poren}/V_{Membran}$ [-]	-	-
η dynamische Viskosität [Pa·s]	***Viskosität von Wasser***	~0.02 K^{-1}
l Porenlänge [m]	*Ausdehnung von Polymere*	*$5 \cdot 10^{-5}$ - $2 \cdot 10^{-4}$* K^{-1}

Frequency of chemical maintenance clean on Zenon





Q_{max}: 3 m^3/h; Q_{avg}: 1.2 m^3/h
$Q_{sludge\ recycle}/Q_{avg} = 2$
$HRT_{before\ membrane}$: 3.5 h
HRT_{tot} = 15 h



$HRT_{before\ membr.}$: 1 h
HRT_{tot} = 7.5 h

Anaerobic membrane bioreactor for industrial wastewater treatment

Marco Ferraris[1], Carolina Innella[1], Francesca Malpei[2], Alfieri Pollice[3]

[1] ENEA, Sezione Sviluppo tecnologie e processi di recupero e riuso, S.S. 106 Jonica km 419+500 Rotondella (MT), Italy.
[2] POLITECNICO DI MILANO, DIIAR, Sezione Ambientale Piazza Leonardo da Vinci 32, Milano, Italy.
[3] IRSA-CNR, Viale F. De Blasio 5, 70123 Bari, Italy.

Research field:

TREATMENT OF MID-HIGH ORGANIC LOAD INDUSTRIAL WASTEWATER

Current technologies are based on anaerobic digestion process:

- Upflow Anaerobic Sludge Blanket (UASB),
- Anaerobic filters,
- Anaerobic baffled reactor etc.

They use different principles to retain biomass and augment SRT

Problems

- Can be used only for wastewaters with low suspended solids content.
- Low process stability due to potential loss of biomass with inflow fluctuations.

Membrane filtration can solve these problems

Advantages of using membrane filtration integrated with anaerobic digestion

- Biomass concentration up to 30 g/L SST;
- Completely independent SRT and HRT;
- Outflow without suspended solids in every load conditions (process stability)
- Selection of biomass based on growth rates instead of sedimentability (suitability for slow growing organisms)

Coupling membrane filtration to anaerobic process

First studies are based on “side-stream” configuration and cross-flow membranes.

Results were non encouraging because:

- Anaerobic biomass activity appeared influenced by the extreme hydrodynamic conditions occurring in cross-flow filtrations.
- Limited filterability of the anaerobic mixed liquor.

Research conducted by ENEA

Application of submerged membrane because:

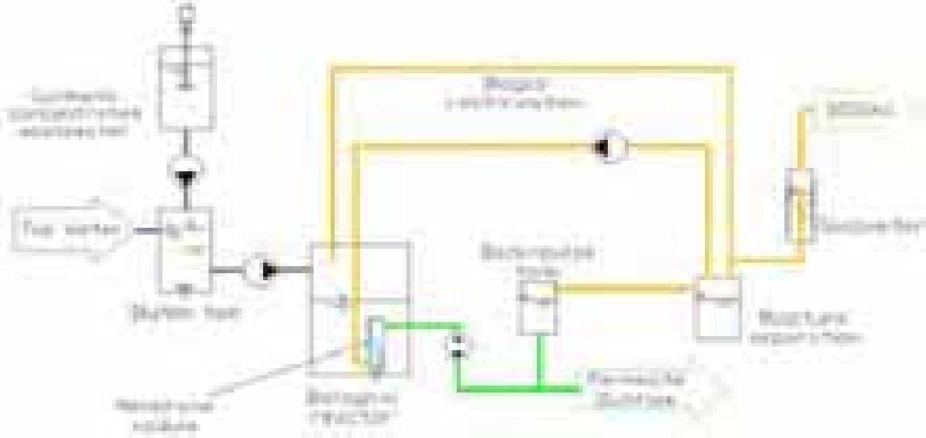
- Less mechanical stress on biomass;
- Possibly better filtration if less cell disruption occurs;
- Submerged MBR are outcompeting side stream systems due to favourable energy balance.

PROBLEM
Air sparging below the membrane module for cake removal is not suitable for anaerobic processes.

SOLUTION

Biogas can be recirculated and sparged instead of air.

Pilot plant scheme



Plant characteristics

- Completely mixed reactor.
- Thermostatic control (mesophilic conditions).
- Volume of reaction 10 – 30 Litres.
- Total volume 45 Litres
- Membrane: ZENON hollow fibre.
- Biogas recirculation at the bottom of the reactor for membrane cleaning and mixing.

First experimental campaign (13/07/05 – 02/08/05)

Biological process setup	Wastewater:	synthetic (glucose + mineral medium) 3000 gCOD/L
	Inoculum:	UASB granular sludge (start conc. 10 gSSV/L)
	Volume of reaction:	20 L
	Temperature	37°C
	Organic load:	1.5 g/L*Day
	SRT:	No sludge wastage
	HRT:	48 hours
Filtration setup	Permeation flux:	10.4 LMH
	Permeation duration:	9 minutes
	Backpulse flux:	15.1 LMH
	Backpulse duration:	0.5 minutes
	Biogas sparging:	15 NL/min

Results of first experimentation

- Verified hydraulic and biological functionality of the system.
- Very fast start up of the anaerobic process.
- High COD removal efficiency (up to 99% after 10 days).
- High methane yield 0,32 NL CH_4/gCOD (near theoretic value).

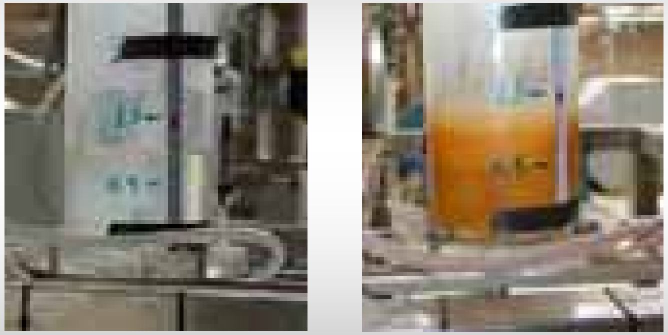
HOWEVER

The experiment was stopped after 20 days due to fouling problems

Loss of the granular structure of the sludge

Fouling was probably due to precipitates

Precipitate formation in backpulse tank (first experimentation)



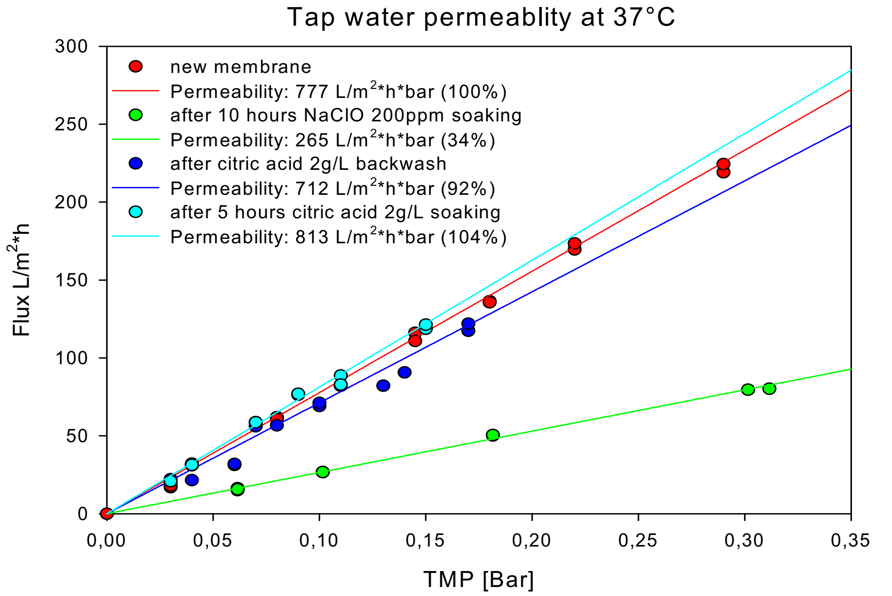
Pictures documenting the evolution of sludge features

Inoculum

After 6th day

After 20th day

Permeability recovery cycle (first experimentation)



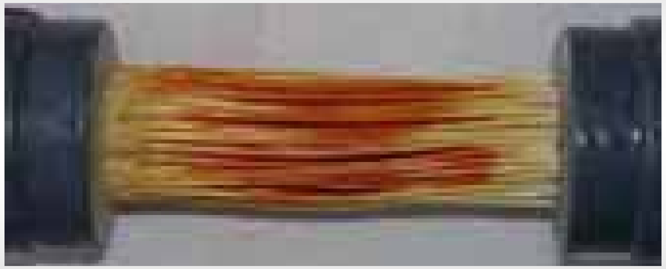
Pictures documenting the status of the membrane

After soaking 10 hours in sodium hypoclorite (300 ppm)

Just out the reactor

After soaking 5 hours in citric acid (2000 ppm)

Pictures documenting the status of the membrane



After soaking 10 hours in sodium hypoclorite (300 ppm)

Pictures documenting the status of the membrane

After soaking 5 hours in citric acid (2000 ppm)

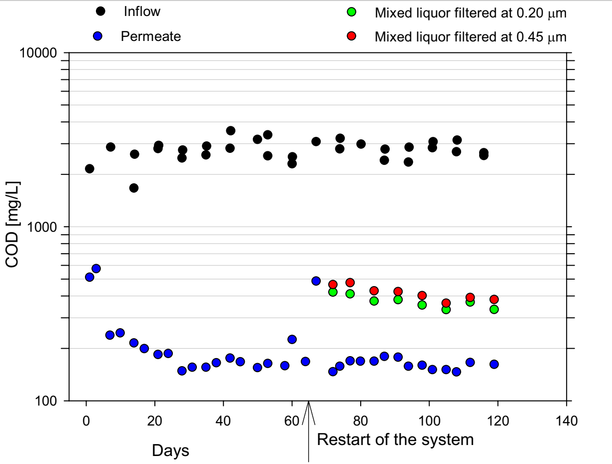
Second experimental campaign (27/02/06 – in progress)

Biological process setup	Wastewater:	synthetic (glucose + meet extract + yeast extract) 3 g COD/L (1.4 g/L, 2.3 g/L, 0.3 g/L respectively)	
	Inoculum:	sludge from previous experiment	
	Inoculum conc.:	Start at 5.5 gSSV/L	↓
	Volume of reaction:	15 L	↓
	Temperature	37°C	=
	Organic load:	1.5 g/L*Day	=
	SRT:	100 Day (second part of experiment)	
	HRT:	48 hours	=
Filtration setup	Permeation flux:	8.4 LMH	↓
	Permeation duration:	6 minutes	↓
	Backpulse flux:	12.1 LMH	↓
	Backpulse duration:	0.5 minutes	=
	Biogas sparging:	20 NL/min	↑

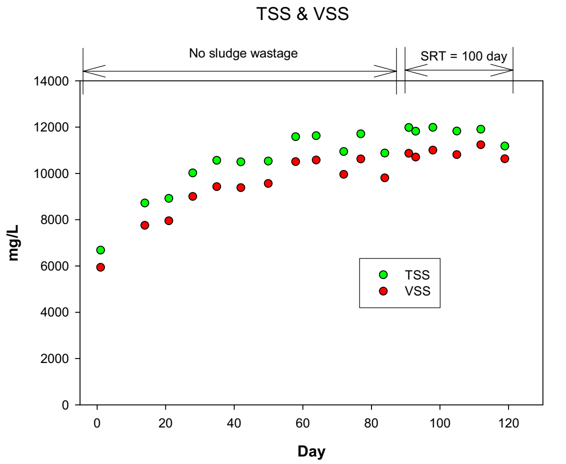
Results of the second experiment (in progress)

- No problems with precipitates are being observed;
- The TMP is stable and quite low (2 kPa) with a flux of 8.4 LMH, despite doubling of biomass concentration (sludge growth from 5.5 to 12.0 gTSS/L);
- COD abatement close to 94% (permeate COD about 160 mg/L);
- VFA were detectable only during the first days after start up (no accumulation);
- Biogas production is stable and the methane yield is close to 0,32 $NLCH_4/gCOD$;
- The methane concentration in biogas is higher than 75%.

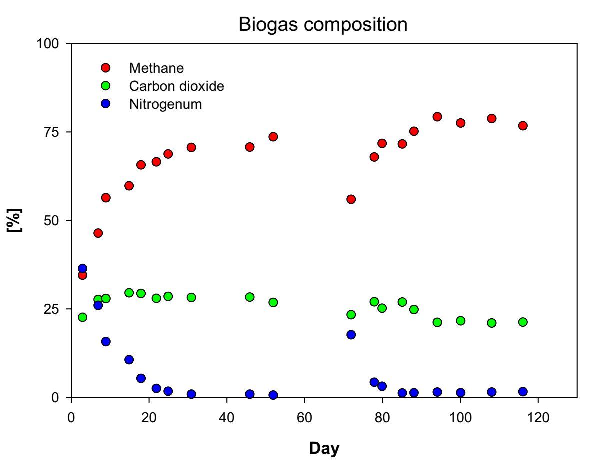
Results of the second experiment (in progress)



Results of the second experiment (in progress)



Results of the second experiment (in progress)



Problem due to air accidentally sparged on day sixty

- Overall, the biological processes did not appear to be seriously damaged

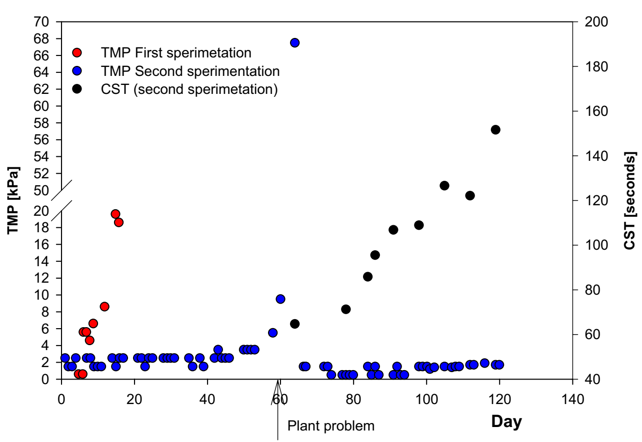
BUT

- Filterability drop occurred upon restart of the system;
- Formation of thick scum suggested changes of the mixed liquor (never previously observed).

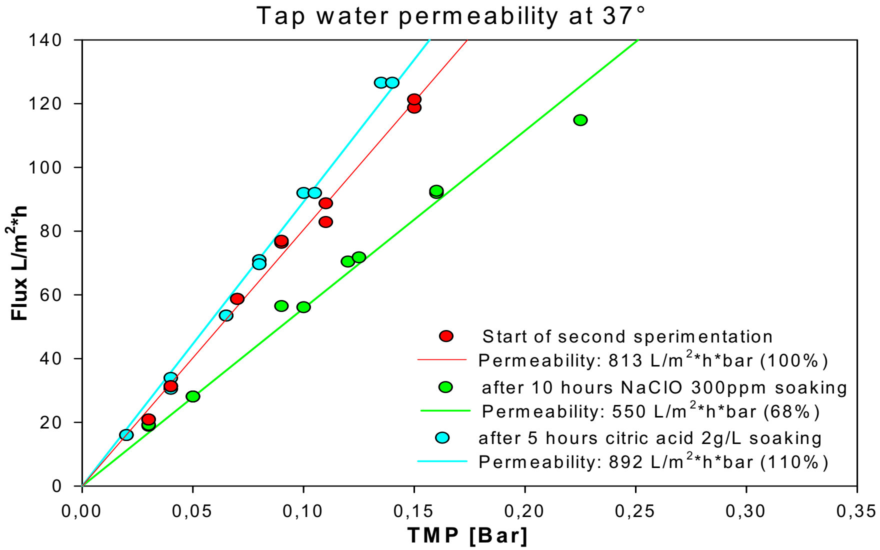
Possible cause

- Release of intracellular material due to lysis caused by the environmental stress.

Results of the second experiment (in progress)



Permeability recovery cycle (second experimentation)



Conclusions

Treatment system

- The feasibility of using submenrged membranes in anaerobic bioreactors was shown.
- The anaerobic process was stable and complete.
- High COD removal yield was reached after few days from start up.
- The permeate is totally free of TSS and the COD is very low.
- The use of sparged biogas to limit cake formation is proving to be effective.
- Anaerobic mixed liquor with TSS concentrations up to 12 g/L have shown very good filterability (comparable with aerobic systems).

Conclusions

Membrane fouling/cleaning

- Wastewater composition is crucial for precipitate formation.
- Granular structure of the sludge can hardly be maintained in these systems.
- In spite of this, very high filterability was observed.
- Possible effects of biomass stress on membrane fouling were evaluated when the accident occurred.
- Membrane fouling was recovered with adequate chemical cleaning.
- Fouling seemed to be caused by both organic and inorganic compounds.

Further assessment will point out on:

- Evaluation of the system under different organic loads.
- Definition of other possible causes of biomass stress (load, temperature, toxic compounds) and their effects on fouling.
- Better characterisation of fouling (EPS,SMP,precipitates, etc.).

Thank you for your attention !

Synthetic wastewater composition (first experiment)

Element/substance	Concentration [mg/L]	Introduced as
Glucose	3000 (as COD)	Destrosio
K	200	KCl
Na	150	$NaHCO_3$
Mg	108	$MgCl_2•6H_2O$, $MgSO_4•7H_2O$
Ca	100	$CaCl_2•2H_2O$
N	80	NH_4Cl
P	15	Na_2HPO4
Fe	10	$FeCl_2•4H_2O$
S	10	$MgSO_4•7H_2O$
Se	0,08	$Na_2SeO_3•5H_2O$
Mo	0,05	$Na_2MoO_4•2H_2O$
Mn	0,02	$MnSO_4•H_2O$
W	0,02	$Na_2WO_4•2H_2O$
Co	0,02	$CoSO_4•H_2O$
Ni	0,02	$NiCl_2•6H_2O$
Cu	0,02	$CuCl_2•2H_2O$
Zn	0,02	$ZnSO_4•7H_2O$
B	0,02	H_3BO_3

The VITO Fouling Measurement (VFM) as a basis for an on-line fouling sensor for advanced MBR process control ?

VITO
Flemish Institute for Technological Research
Mol
Belgium
Etienne Brauns, Heleen De Wever, Erwin Van Hoof, Bart Molenberghs,
Pieter Lens, Rob Muyshondt, Louis Raats

Topics

(Note : as indicated in the Abstract, the presentation today is mainly about VFM for non-MBR filtration but nevertheless informative)

- Short history of the origin of the VFM
- Basic characteristics of the dead-end VFM method
- Some typical VFM-results
- Adaptation of VFM to MBR : concept, set-up and goals

Short history of VFM

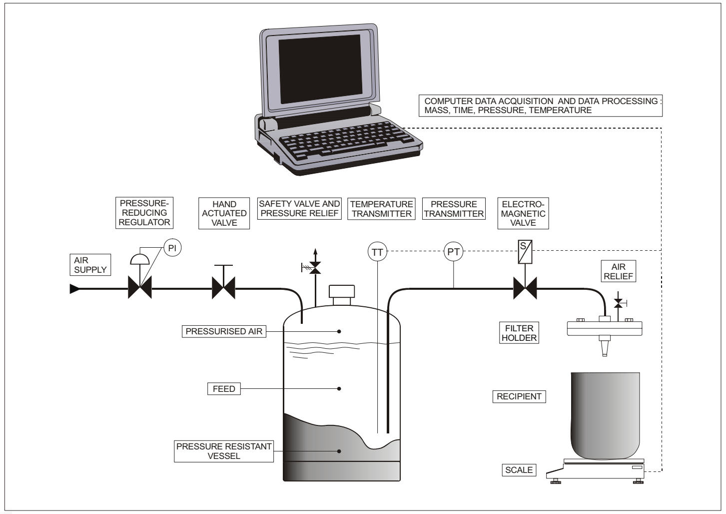
- *Proposition* : within pressure driven membrane filtration there is no universal applicable fouling model which accurately calculates flux decline as a result of the complex build-up of feed constituents, as retained by a membrane
- *Conclusion* : for feeds with a complex composition and a lack of an adequate fouling model, a characterization method could :
  - give useful information on the filtration (fouling) behavior
  - be the basis for an on-line sensor to optimize the filtration (24 h on 24 h)

Short history of VFM, index methods

- SDI : ASTM D4189 ; “Standard Test Method for Silt Density Index (SDI) of Water
- “Water is passed through a 0.45 µm membrane filter at a constant applied gage pressure of 207 kPa (30 psi), and the rate of plugging of the filter is measured.
  - t_i = initial time to collect 500 (250 or 100) ml
  - t_f = time to collect 500 (250 or 100) ml after test time T
  - T = total elapsed flow time (15, 10 or 5 minutes)
- Done manually by technician : expensive

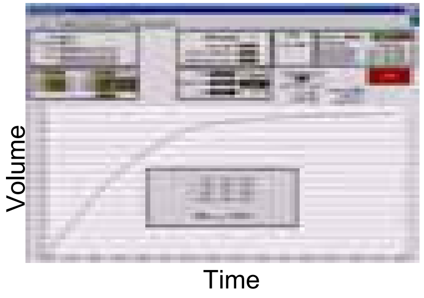
$$SDI_T = \frac{100.\left[1 - \frac{t_i}{t_f}\right]}{T}$$

Short history of VFM, index methods



Short history of VFM, index methods

Automated SDI measurement at Vito



	100 ml	250 ml	500 ml
5	5.10	5.18	5.33
10	6.24	6.38	6.64
15	6.29	6.29	6.42

$$\mathrm{SDI}_{10\text{-}500} = 6.64$$

Practice : a large number of the measurements turned out to be not accepted by ASTM D4189 when strictly applying the rules 3, 4 and 9

Short history of VFM, index methods

- MFI (Modified Fouling Index) is based on resistance in series model

$$\frac{1}{A}\cdot\frac{dV}{dt}=\frac{\Delta P}{\eta}\cdot\frac{1}{(R_m+R_f)}$$

- V = permeate volume ; t = time
- dV/dt = flow
- A = membrane effective surface area
- ΔP = transmembrane pressure drop
- η = absolute viscosity
- R_m = membrane resistance
- R_f = all "additional resistance ("fouling)

Short history of VFM, index methods

- when re-arranging the basic equation into

$$dt=\left(\frac{\eta.R_m}{\Delta P.A}+\frac{\eta.R_f(V)}{\Delta P.A}\right).dV$$

- one obtains by integration :

$$\int_0^t dt=\int_0^V \frac{\eta.R_m}{\Delta P.A}.\,dV+\int_0^V \frac{\eta.R_f(V)}{\Delta P.A}.dV=\frac{\eta.R_m}{\Delta P.A}.\int_0^V dV+\frac{\eta}{\Delta P.A}.\int_0^V R_f(V).dV$$

$$\int_0^t dt=\frac{\eta.R_m}{\Delta P.A}.V+\frac{\eta}{\Delta P.A}.\boxed{\int_0^V R_f(V).dV}\leftarrow ?$$

- in the MFI theory the assumption is made that the (cake) fouling resistance is proportional to the permeate volume :

$$R_f(V)=R_{cake}=const.V$$

Short history of VFM, index methods

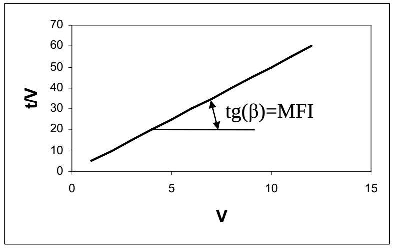
- in the case that this is true :

$$\int_0^t dt = \frac{\eta . R_m}{\Delta P . A} . V + \frac{\eta}{\Delta P . A} . \int_0^V const . V . dV = \frac{\eta . R_m}{\Delta P . A} . V + \frac{\eta . const}{\Delta P . A} . \int_0^V V . dV$$

$$t = \frac{\eta . R_m}{\Delta P . A} . V + (\frac{\eta . const}{\Delta P . A}) . \frac{V^2}{2}$$

$$\frac{t}{V} = \frac{\eta . R_m}{\Delta P . A} + (\frac{\eta . const}{2 . \Delta P . A}) . V$$

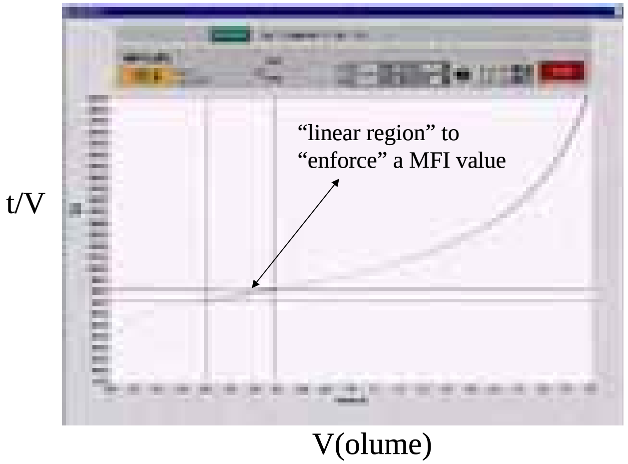
$$\frac{t}{V} = \frac{\eta . R_m}{\Delta P . A} + MFI . V = a + MFI . V$$



MFI type of fouling : t/V versus V should be a straight line and the tangent is equal to MFI. If this is NOT the case, then the assumption $R_f(V)$=const.V was incorrect

Short history of VFM, index methods

- MFI theory versus practice



Short history of VFM, index methods

Quick note on SUR index :

$$\left.\begin{aligned} SUR &= \frac{d(\frac{t}{V})}{dV} . \frac{2.\Delta P.A^2}{\eta} \\[2em] \frac{d(\frac{t}{V})}{dV} &= (\frac{\eta . I}{2 . \Delta P . A^2}) = MFI \end{aligned}\right\} \quad SUR = MFI . \frac{2.\Delta P.A^2}{\eta}$$

Short history of VFM, index methods

- For (mostly) non-linear cases, the enforced MFI value thus represents only a fraction of the total fouling behavior, reducing the complex fouling into one number, as the SDI method does
- A non-linear t/V versus V curve even indicates that the assumed $R_f(V)$=const.V is not true in such a case and therefore the theoretical/mathematical background does not hold any longer in such a case
- In fact an index is a simple fouling “model equation “y=a approach
- As a result there is a potential loss of information from the measured V versus t data, when only communicating the single SDI or MFI-value
- As a result of all this, a pragmatic approach was looked into at VITO : VFM (VITO fouling measurement)

Basic VFM characteristics

- VFM is still based on resistance in series model

$$\frac{dV}{dt} = (\frac{A \cdot \Delta P}{\eta}) \cdot \frac{1}{(R_m + R_f)} = (\frac{A \cdot \Delta P}{\eta}) \cdot \frac{1}{R_{tot}}$$

V = permeate volume (m)
t = time (s)
ΔP = transmembrane pressure drop (Pa)
η = absolute viscosity (kg/m.s)
R_m = membrane resistance (m^{-1})
R_f = all additional resistance from the fouling (m^{-1})
R_{tot} = total hydraulic resistance (m^{-1})
A = membrane surface area (m)

Basic VFM characteristics

- integration :

$$\int_0^t dt = \frac{\eta \,.\, R_m}{\Delta P \,.\, A} .V + \frac{\eta}{\Delta P \,.\, A} . \int_0^V \boxed{R_f(V)\,.\,dV}$$

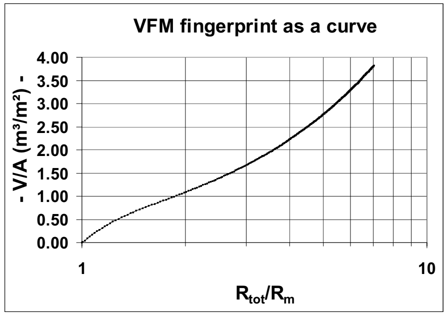
- exact function R_f (V) must be known to finish the integration
- R_f (V) is very complex/unknown in real situations, so the integration halts right there
- VFM pragmatically extracts from the hundreds of discrete samples (V_i,t_i) the R_f (V) information, as a fingerprint V/A versus R_{tot}/R_m format.
- VFM concept is thus a “multiple value method, not a simplified “one index value fouling measurement method
- All fouling information is retained (even time)

Basic VFM characteristics

- E. Brauns, E. Van Hoof, B. Molenberghs, C. Dotremont, W. Doyen, R. Leysen, A new method of measuring and presenting the membrane fouling potential, Desalination 150, (2002) , p. 31-43
- E. Brauns, K. Faes, E. Van Hoof, W. Doyen, Ch. Dotremont, R. Leysen, The measurement and presentation of the fouling potential with a new method, Proceedings International Conference Membranes in Drinking and Industrial Water Production (MDIW) Mülheim (Germany), 23-26/9/2002 (IWW Series Book) and Water Science and Technology - vol. 37a, pp. 381-388 (2002)
- E. Brauns, D. Teunckens, C. Dotremont, E. Van Hoof, W. Doyen, D. Vanhecke, Dead end filtration experiments on model dispersions : comparison of VFM data and the Kozeny-Carman model, Desalination 177 (2005) p 303-315

Basic VFM characteristics

VFM graph format

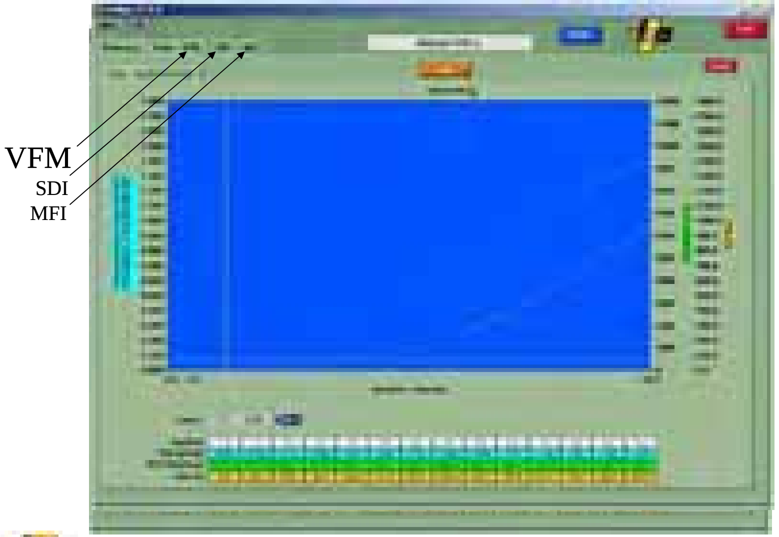


- Horizontal VFM curve:
  low throughput = strong fouling
- Vertical VFM curve:
  high throughput = low fouling
- VFM curve as a (standard) fouling s fingerprint

VFM table format, including time

R_{tot}/R_m	1	2	3	4	5	6	7	8	9	10
V/A (m³/m²)	0	1.24	1.64	1.88	2.07	2.22	2.37	2.49	2.61	2.72
t (seconds)	*0*	*292*	*455*	*596*	*737*	*885*	*1039*	*1197*	*1370*	*1550*
t (minutes)	*0*	*4.87*	*7.58*	*9.93*	*12.3*	*14.75*	*17.32*	*19.95*	*22.8*	*25.8*

Basic VFM characteristics



Some typical VFM results

Code	Type	Description
A	Surface water	Water from different canals. Stored in a reservoir of 6.000.000 m Mean residence time of about 8 months Micro sieved at 35 µm
B	Groundwater	As such , no pre-filtration or treatment
C	Well water	As such , no pre-filtration or treatment
D	Canal water	Extracted from canal, then pre-filtered at 300 µm

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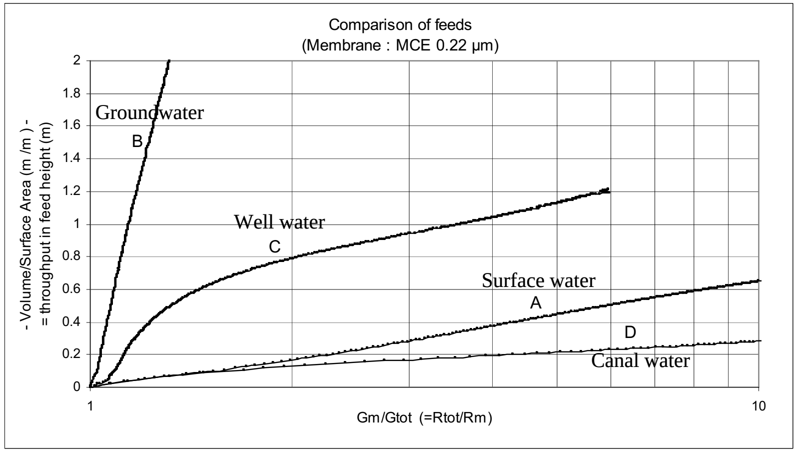
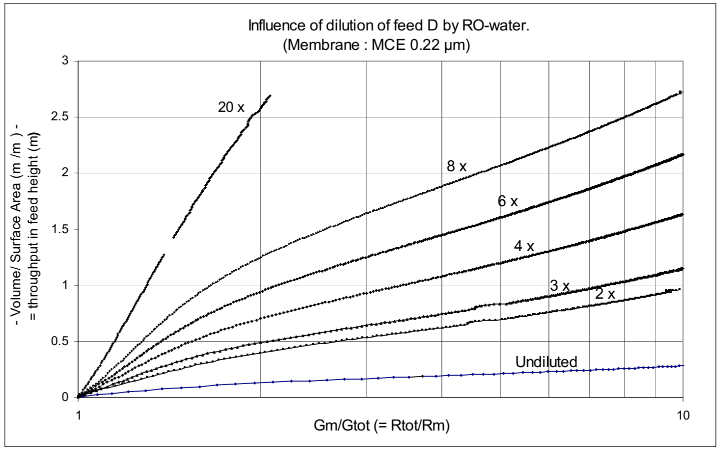
Some typical VFM results



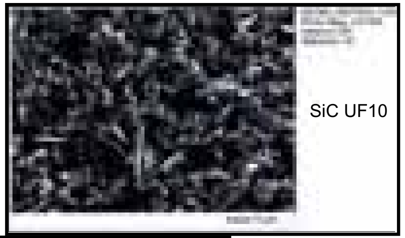
Some typical VFM results



Kozeny-Carman

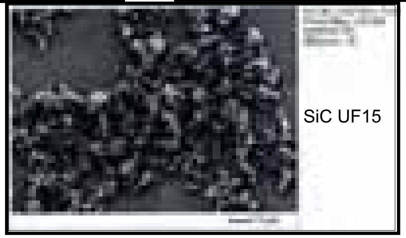
E. Brauns, D. Teunckens, C. Dotremont, E. Van Hoof, W. Doyen, D. Vanhecke, Dead end filtration experiments on model dispersions : comparison of VFM data and the Kozeny-Carman model, Desalination 177 (2005) p 303-315


SiC UF05


SiC UF10

UF = Ultra Fine

H.C. Starck


SiC UF15

SiC UF powder characteristics

Type	UF05	UF10	UF15
BET Specific surface (m /g)[1]	4 - 6	9 - 11	14 - 16
BET Specific surface (m /g)[2]	4.73	9.06	15.1
Particle size (µm) at fraction 90 % smaller than [1a]	4.4	1.8	1.0
Particle size (µm) at fraction 50 % smaller than [1a]	1.4	0.7	0.55
Particle size (µm) at fraction 10 % smaller than [1a]	0.3	0.2	0.1

(1) As specified by H.C.Starck (a = laser diffraction)
(2) As measured at Vito

Kozeny-Carman

$$R_f = k_c \times S_0^2 \times \frac{(1-\varepsilon)^2}{\varepsilon^3} \times H$$

- k_c is the Kozeny constant
- S_0 is the specific surface of the powder on a volume basis (m²/m³)
- ε is the porosity (void fraction ; no units) of the cake
- H is the height (thickness) (m) of the cake

$$H = \frac{V \times c_{SiC}}{\rho_{app} \times S_m} = \frac{V \times c_{SiC}}{3210 \times (1-\varepsilon) \times S_m}$$

- V = volume of permeate
- c_{SiC} = dispersion concentration
- ρ_{app} = apparent density
- ε = porosity
- S_m = membrane surface area

$$R_f = k_c \times S_0^2 \times \frac{(1-\varepsilon)}{\varepsilon^3} \times \frac{V \times c_{SiC}}{3210 \times S_m}$$

Kozeny- constant

Researcher	Material	Value of k_c
Uchikoshi	Zirconia powder suspension A	5.8 to 7.4
Uchikoshi	Zirconia powder suspension B	3.8
Uchikoshi	Alumina powder	4.1 to 5.6
Sobue	Silicon powder	6.2

Originally : Kozeny "constant was considered to be equal to 5

Kozeny-Carman and VFM

Index	B	C	D	E	F	G	H
k_c	5	5	5	5	5	4	6
ε	0.40	0.45	0.50	0.55	0.60	0.50	0.50

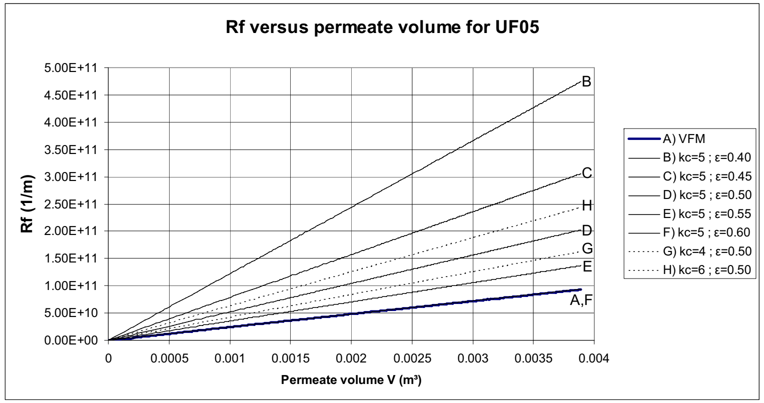
$\underbrace{\text{B, C, D}}_{\text{Acceptable } \varepsilon \text{ values}}$ $\underbrace{\text{E, F}}_{\text{Improbable } \varepsilon \text{ values}}$ $\underbrace{\text{G, H}}_{\text{Effect of } k_c}$

Acceptable ε values

Improbable ε values

Effect of k_c

Kozeny-Carman and VFM



MBR-oriented VFM sensor

- Adaptations were needed : cross-flow (aeration), low pressure range, sludge
- As for now: tubular membrane, inside-out
- Aeration: slug-shaped air bubbles

- Goal : determination of “reversible part $R_{f,rev}$ and “irreversible part $R_{f,irr}$

$$\begin{tikzcd}
 & R_{f,rev}(V) \\
R_f(V) \arrow[ur] \arrow[dr] & \\
 & R_{f,irr}(V)
\end{tikzcd}$$

  - $R_{f,rev}$: control of mechanical cleaning : e.g. aeration, relaxation, backpuls
  - $R_{f,irr}$: control of chemical cleaning

Important note : “irreversible here includes “sticking fouling which can <u>only</u> be removed by chemical cleaning.

MBR-oriented VFM sensor

- MBR-VFM envisages two VFM graphs
  - “reversible fouling : V/A versus $R_{tot,rev}/R_m$ graph
  - “irreversible fouling : V/A versus $R_{tot,irr}/R_m$ graph
- if proven : implementation as an online sensor in an advanced control system (ACS)

MBR-VFM slug flow

Aeration with slug type air bubbles

MBR-VFM LabVIEW program

MeFiAS

- MeFiAS : sophisticated software which was developed at VITO for the control of pressure driven membrane filtration applications (about 40 licences over the world)
- universally applicable with a central universal software “core
- written under LabVIEW
- within Amedeus the LabVIEW fuzzy module will be used to construct the ACS : expertise system on top of MeFiAS control system

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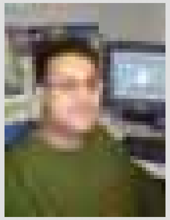
MBR-VFM Outlook

- Setting up of a standard MBR-VFM protocol is a priority
- Extensive MBR-VFM protocol testing needed : start of a thesis student (university grade ; bio-engineer) at VITO early august 2006
- Correlation of fouling data with operational conditions : ACS based on expertise rules and, if proven, on-line MBR-VFM sensor data as input to the MeFiAS based advanced control system

Thank you

Improving the Design and Efficiency of MBR Plant by using Modelling, Simulation and Laboratory Analysis

Parneet Paul
Water Software Systems
De Montfort University



Our industrial collaborators:

- Aquabio – design & commission industrial sidestream configuration MBRs using Jetox aeration and tubular non-ceramic membranes.
- ITT Sanitaire – design & commission industrial submerged MBRs with dead end Puron hollow fibres.
- Water Service Northern Ireland – operate municipal submerged MBRs using Kubota flat plate membranes.

Project Aims

What are we trying to achieve?

- Investigate changes in biomass constituent components in order to better understand its effect on MBR filterability & membrane fouling.
- Creation of a computer model to predict MBR filterability and membrane fouling based upon the above studies.
- Use of the computer model for enhanced MBR design….
- Use of the computer model for improved MBR operation and control.….

Why do we use mathematical modelling?

- **to improve understanding of the process**
- **to optimise process design/operating conditions**
- **to design a control strategy for the process**
- **to train operating personnel**

What is mathematical process modelling?

A mathematical model is:

> *"a representation of the essential aspects of an existing system (or a system to be constructed) which represents knowledge of that system in a usable form"*

- Everything should be made as simple as possible, but no simpler.

General Modelling Principles

- **The model equations are at best an approximation to the real process.**
- ***Adage*: "All models are wrong, but some are useful."**
- **Modelling inherently involves a compromise between model accuracy and complexity on one hand, and the cost and effort required to develop the model.**
- **Process modelling is both an art and a science. Creativity is required to make simplifying assumptions that result in an appropriate model.**
- **Dynamic models of chemical processes consist of ordinary differential equations (ODE) and/or partial differential equations (PDE), plus related algebraic equations.**

Modelling Approaches - 1

- **Physical/chemical (fundamental, global)**
    - Model structure by theoretical analysis
        - Material/energy balances
        - Heat, mass, and momentum transfer
        - Thermodynamics, chemical kinetics
        - Physical property relationships
    - Model complexity must be determined (assumptions)
    - Can be computationally expensive (not real-time)
    - May be expensive/time-consuming to obtain
    - Good for extrapolation, scale-up
    - Does not require experimental data to obtain (data required for validation and fitting)
    - Conservation Laws

Approach 1 - Conservation Laws

- **Conservation of Mass**

$$\left\{\begin{matrix}\text{rate of mass}\\ \text{accumulation}\end{matrix}\right\}=\left\{\begin{matrix}\text{rate of mass}\\ \text{in}\end{matrix}\right\}-\left\{\begin{matrix}\text{rate of mass}\\ \text{out}\end{matrix}\right\}$$

- **Conservation of Component i**

$$\left\{\begin{matrix}\text{rate of component i}\\ \text{accumulation}\end{matrix}\right\}=\left\{\begin{matrix}\text{rate of component i}\\ \text{in}\end{matrix}\right\}$$

$$-\left\{\begin{matrix}\text{rate of component i}\\ \text{out}\end{matrix}\right\}+\left\{\begin{matrix}\text{rate of component i}\\ \text{produced}\end{matrix}\right\}$$

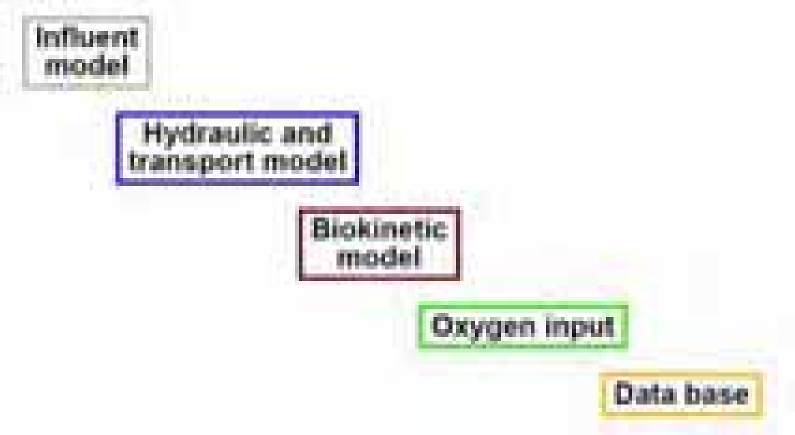
Modelling Approaches - 2

- **Black box (empirical)**
  - Large number of unknown parameters
  - Can be obtained quickly (e.g., linear regression)
  - Model structure is subjective
  - Dangerous to extrapolate
- **nonlinear models** such as neural nets are becoming popular (automatic modeling)

Modelling Approaches - 3

- **Semi-empirical**
  - Compromise of first two approaches
  - Model structure may be simpler
  - Typically 2 to 10 physical parameters estimated (nonlinear regression)
  - Good versatility, can be extrapolated
  - Can be run in real-time
  - linear regression
  - nonlinear regression
  - number of parameters affects accuracy of model, but confidence limits on the parameters fitted must be evaluated
  - objective function for data fitting – minimize sum of squares of errors between data points and model predictions (use optimization code to fit parameters)

What are the Components of a Fully Descriptive Model?



What is a Biokinetic Model?

- models for biological reactions *r* in the tank needed:
- growth of biomass: $r_B = r_{\max} \frac{C_s}{K_s + C_s} C_B$ (Monod-Kinetic)
- decay of biomass: $r_B = -b_{\max} C_B$
- substrate utilization: $r_S = -\frac{1}{Y} r_B$ ratio biomass growth / substrate removal

r_{max}- max. growth rate per day
C_s - growth limiting substrate concentration
K - growth half time constant
b_{max}- max. decay rate per day
Y - Yield - coefficient (proportional factor)

What Biokinetic Models are available?

– for example, *Activated Sludge Model No.1 (ASM1)*

Bioreactor Tanks

- full **ASM 1 by IAWQ Task Group:** **8 processes** (hydrolysis, biomass grow / decay, ammonification)
  13 components - **7** soluble (**S**), **5** solids (**X**)

$$\frac{dC}{dt} = \frac{Q_{in}}{V}(C_{in} - C(t)) + r(t)$$

- **tank well-mixed, constant volume:**
  (first order lag behaviour)
- C - 13 dimensional state vector, r(t) conversion rate vector of ASM1 process matrix
- kinetic / stoichiometric parameters for V = 15° C

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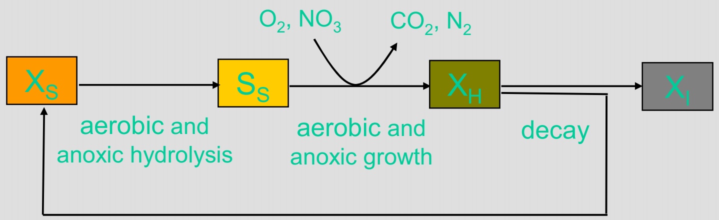
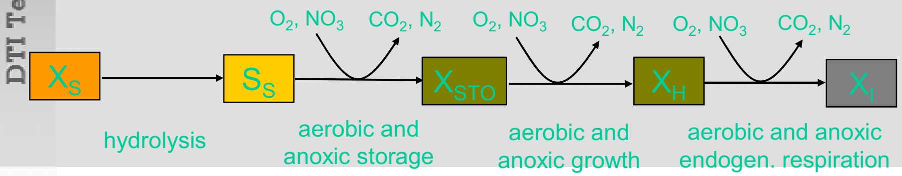
13 ASM1 Model Variables

1) S_I soluble inert COD concentration
2) S_{ND} soluble organic nitrogen concentration
3) S_{NH} ammonium concentration
4) S_{NO} nitrate and nitrite nitrogen concentration
5) S_O dissolved oxygen concentration
6) S_S readily biodegradable COD concentration
7) S_{ALK} alkalinity concentration measured as CaCO3
8) X_{BA} autotrophic biomass concentration
9) X_{BH} heterotrophic biomass concentration
10) X_P biomass decay particulate byproducts
11) X_I particulate inert COD concentration
12) X_{ND} particulate organic nitrogen concentration
13) X_S slowly biodegradable COD concentration

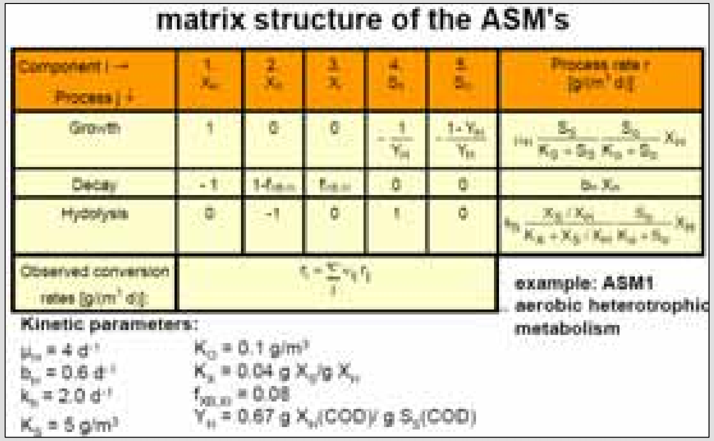
Degradation of COD in ASM1



Degradation of COD in ASM3



ASM Matrix Notation



matrix structure of the ASM's

Component i → Process j ↓	1 X_H	2 X_S	3 X_I	4 S_S	5 S_O	Process rate r_j [g/m³ d]
Growth	1	0	0	$-\frac{1}{Y_H}$	$-\frac{1-Y_H}{Y_H}$	$\mu_H \frac{S_S}{K_S+S_S}\frac{S_O}{K_O+S_O}X_H$
Decay	-1	$1-f_{XI,H}$	$f_{XI,H}$	0	0	$b_H X_H$
Hydrolysis	0	-1	0	1	0	$k_h \frac{X_S/X_H}{K_X+X_S/X_H}\frac{S_O}{K_O+S_O}X_H$
Observed conversion rates [g/m³ d]:	$r_i = \sum_j \nu_{ij} r_j$					

Kinetic parameters:

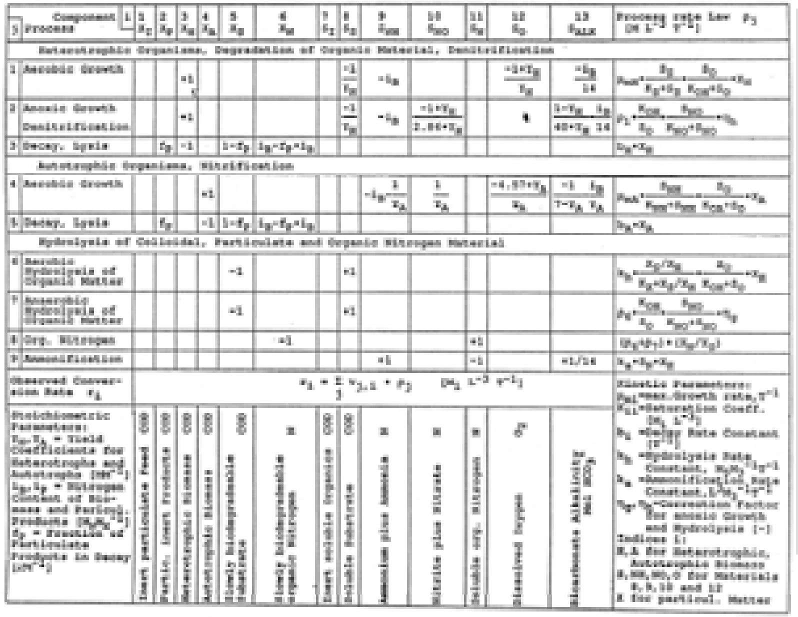
$\mu_H = 4\ d^{-1}$
$b_H = 0.6\ d^{-1}$
$k_h = 2.0\ d^{-1}$
$K_S = 5\ g/m^3$
$K_O = 0.1\ g/m^3$
$K_X = 0.04\ g\ X_S/g\ X_H$
$f_{XI,H} = 0.08$
$Y_H = 0.67\ g\ X_H(COD)/\ g\ S_S(COD)$

example: ASM1 aerobic heterotrophic metabolism

S – soluble waste water components (soluble substrates)

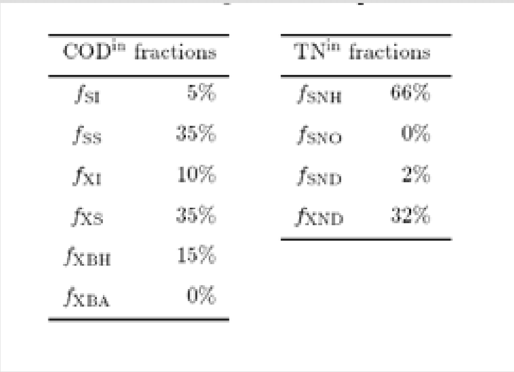
X – solid waste water components (substrates, biomass)

ASM no. 1



j	Component → Process ↓	1 X_I	2 X_P	3 X_H	4 X_A	5 X_S	6 X_N	7 S_I	8 S_S	9 S_{NH}	10 S_{NO}	11 S_N	12 S_O	13 S_{ALK}	Process rate law ρ_j $[M\ L^{-3}\ T^{-1}]$
	Heterotrophic Organisms, Degradation of Organic Material, Denitrification														
1	Aerobic Growth			+1					$-\frac{1}{Y_H}$	$-i_B$			$-\frac{1-Y_H}{Y_H}$	$-\frac{i_B}{14}$	$\mu_{mH}\cdot\frac{S_S}{K_S+S_S}\cdot\frac{S_O}{K_{OH}+S_O}\cdot X_H$
2	Anoxic Growth Denitrification			+1					$-\frac{1}{Y_H}$	$-i_B$	$-\frac{1-Y_H}{2.86\cdot Y_H}$		[illegible]	$\frac{1-Y_H}{40\cdot Y_H}-\frac{i_B}{14}$	$\rho_1\cdot\frac{K_{OH}}{S_O}\cdot\frac{S_{NO}}{K_{NO}+S_{NO}}\cdot\eta_g$
3	Decay, Lysis		f_P	-1		$1-f_P$	$i_B-f_P\cdot i_P$								$b_H\cdot X_H$
	Autotrophic Organisms, Nitrification														
4	Aerobic Growth				+1					$-i_B-\frac{1}{Y_A}$	$\frac{1}{Y_A}$		$-\frac{4.57-Y_A}{Y_A}$	$-\frac{1}{7\cdot Y_A}-\frac{i_B}{14}$	$\mu_{mA}\cdot\frac{S_{NH}}{K_{NH}+S_{NH}}\cdot\frac{S_O}{K_{OA}+S_O}\cdot X_A$
5	Decay, Lysis		f_P		-1	$1-f_P$	$i_B-f_P\cdot i_P$								$b_A\cdot X_A$
	Hydrolysis of Colloidal, Particulate and Organic Nitrogen Material														
6	Aerobic Hydrolysis of Organic Matter					-1			+1						$k_h\cdot\frac{X_S/X_H}{K_X+X_S/X_H}\cdot\frac{S_O}{K_{OH}+S_O}\cdot X_H$
7	Anaerobic Hydrolysis of Organic Matter					-1			+1						$\rho_6\cdot\frac{K_{OH}}{S_O}\cdot\frac{S_{NO}}{K_{NO}+S_{NO}}\cdot\eta_h$
8	Org. Nitrogen						-1					+1			$(\rho_6+\rho_7)\cdot(X_N/X_S)$
9	Ammonification									+1		-1		+1/14	$k_a\cdot S_N\cdot X_H$
	Observed Conversion Rate r_i	$r_i = \sum_j \nu_{j,i}\cdot\rho_j \quad [M_i\ L^{-3}\ T^{-1}]$													Kinetic Parameters: μ_{mi} = max. Growth rate, T^{-1} K_{ii} = Saturation Coeff. $[M_i\ L^{-3}]$ b_i = Decay Rate Constant $[T^{-1}]$ k_h = Hydrolysis Rate Constant, $M_S M_H^{-1} T^{-1}$ k_a = Ammonification Rate Constant, $L^3 M_H^{-1} T^{-1}$ η_g, η_h = Correction Factor for anoxic Growth and Hydrolysis [-] Indices i: H, A for Heterotrophic, Autotrophic Biomass S, NH, NO, O for Materials 8, 9, 10 and 12 X for particul. Matter
	Stoichiometric Parameters: Y_H, Y_A = Yield Coefficients for Heterotrophs and Autotrophs $[MM^{-1}]$ i_B, i_P = Nitrogen Content of Biomass and Partic. Products $[M_N M_S^{-1}]$ f_P = Fraction of Particulate Products in Decay $[MM^{-1}]$	Inert particulate feed COD	Partic. inert products COD	Heterotrophic biomass COD	Autotrophic biomass COD	Slowly biodegradable substrate COD	Slowly biodegradable organic nitrogen N	Inert soluble organics COD	Soluble substrate COD	Ammonium plus ammonia N	Nitrite plus nitrate N	Soluble org. nitrogen N	Dissolved oxygen O_2	Bicarbonate alkalinity Mol HCO_3	

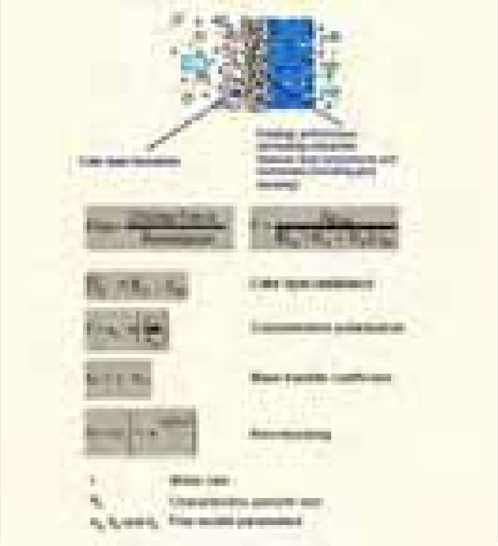
How does the model variables relate to measured variables?



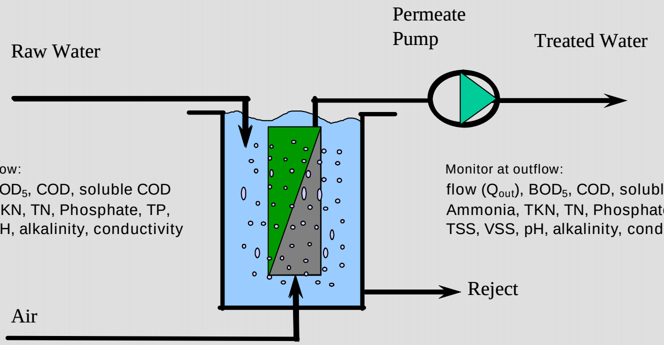
COD^{in} fractions	
f_{SI}	5%
f_{SS}	35%
f_{XI}	10%
f_{XS}	35%
f_{XBH}	15%
f_{XBA}	0%

TN^{in} fractions	
f_{SNH}	66%
f_{SNO}	0%
f_{SND}	2%
f_{XND}	32%

Modelling Filtration Performance



Typical Variables Measured for an MBR

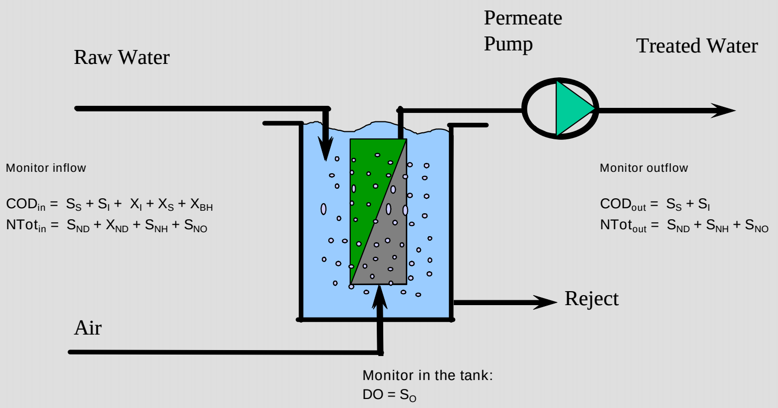


Monitor at inflow:
flow (Q_{in}), BOD_5, COD, soluble COD
Ammonia, TKN, TN, Phosphate, TP,
TSS, VSS, pH, alkalinity, conductivity

Monitor at outflow:
flow (Q_{out}), BOD_5, COD, soluble COD
Ammonia, TKN, TN, Phosphate, TP,
TSS, VSS, pH, alkalinity, conductivity

Monitor in the tank:
DO, MLSS, MLVSS, centipoise viscosity, sludge wastage rate,
Pressure difference across membrane,
microscopic evaluation of biomass

ASM1 Parameters for an MBR model



Raw Water

Permeate Pump

Treated Water

Monitor inflow

$COD_{in} = S_S + S_I + X_I + X_S + X_{BH}$

$NTot_{in} = S_{ND} + X_{ND} + S_{NH} + S_{NO}$

Monitor outflow

$COD_{out} = S_S + S_I$

$NTot_{out} = S_{ND} + S_{NH} + S_{NO}$

Reject

Air

Monitor in the tank:

$DO = S_O$

$$F = \frac{TMP}{\mu\,(Rm + R\,n + Rc)}$$

F = permeate flux, $m^3/m^2/h$
μ = permeate viscosity, Pa.s
TMP = trans-membrane pressure, Pa
Rm = hydraulic resistance, L/m
Rn = irreversible fouling, L/m
Rc = resistance due to cake layer, L/m

Some MBR models developed by previous researchers

- Wintgens, et al – extensive work done on various models based on both ASMs and filtration equations.
- Yan Li, et al – sludge cake growth related to shear indensity distribution.
- Hermanowicz – unified theoretical framework based on particle size.
- Lu, et al – ASM models with UAP / BAP.

- Cinar, et al – artificial neural networks.
- Gehlert, et al – dynamic modelling of UF module.
- Kromkamp, et al – suspension flow model for hydrodynamics and conc. Polar. in MF.

…………I am sure there are many others!

Project Progress to Date

- Historical data collation
- MBR plant site visits
- Procurement of software platforms
- Training courses / networking

Initial data analysis

- Lots of data in some areas but not all relevant
- Paucity of data in other areas
- Will need to design individual sampling programme / campaign based on many factors
- Basically the more info., the easier to calibrate, the more realistic the model, the more useful the simulations……..

MBR plant site visits – Robertson’s Ledbury

Ledbury Plant

Procurement of software platforms

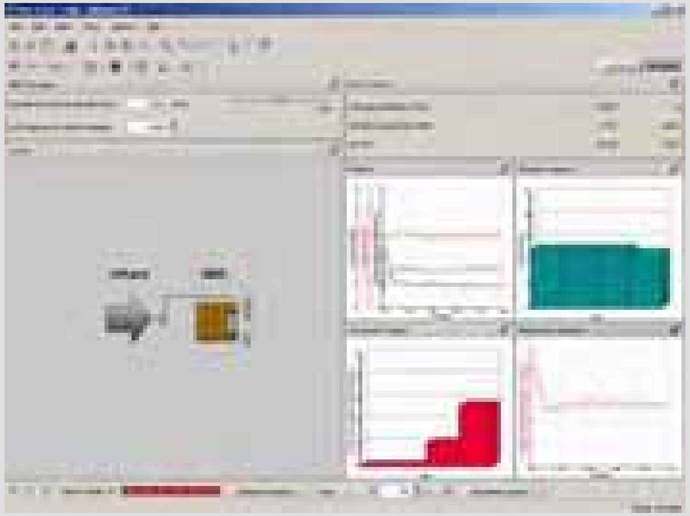
- BioWin 2.0 (EnviroSim)
- GPS-X 5.0 (Hydromantis)

- Aquasim (EAWAG) – research orientated

Research licence copies

(rejected SIMBA, ASIM, West, STOAT, EFOR, etc.)

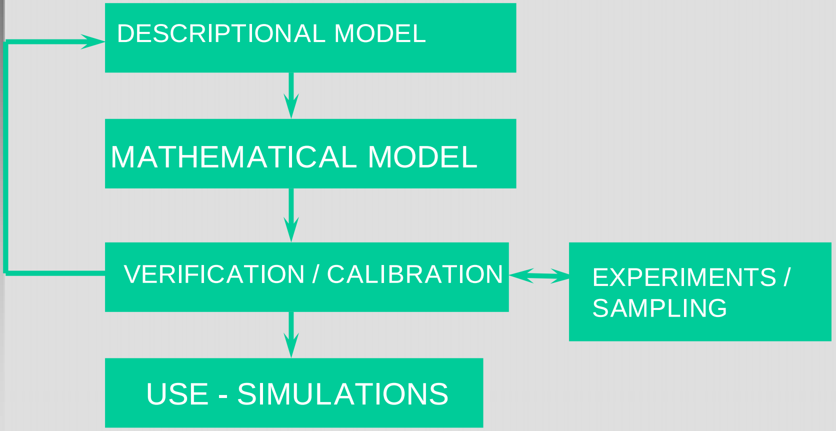
GPS-X Simulator



MODELLING BASICS

- GENERAL SET-UP
- STOICHIOMETRY
- KINETICS
- TRANSPORT PHENOMENA
- MATRIX NOTATION

MODEL BUILDING



DESCRIPTIONAL MODEL

MATHEMATICAL MODEL

VERIFICATION / CALIBRATION

EXPERIMENTS / SAMPLING

USE - SIMULATIONS

GENERAL MODEL SET-UP

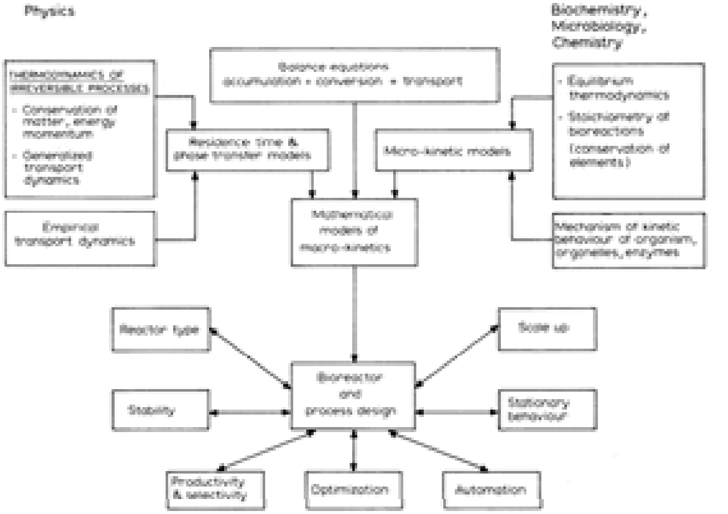


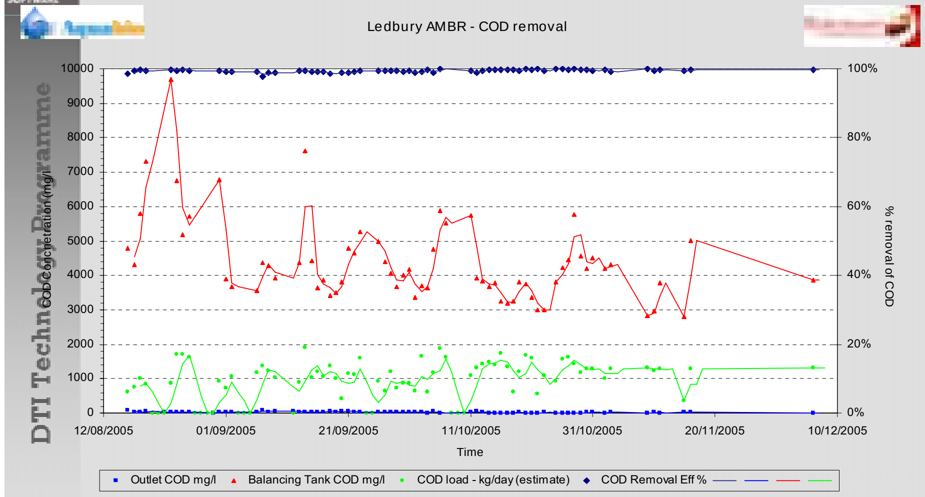
Fig. 1.2. The structure of (bio)chemical reaction engineering. (From Roels, J.A. (1982) J. Appl. Chem. Biotechnol. 32, 59.)

Model Calibration Procedure

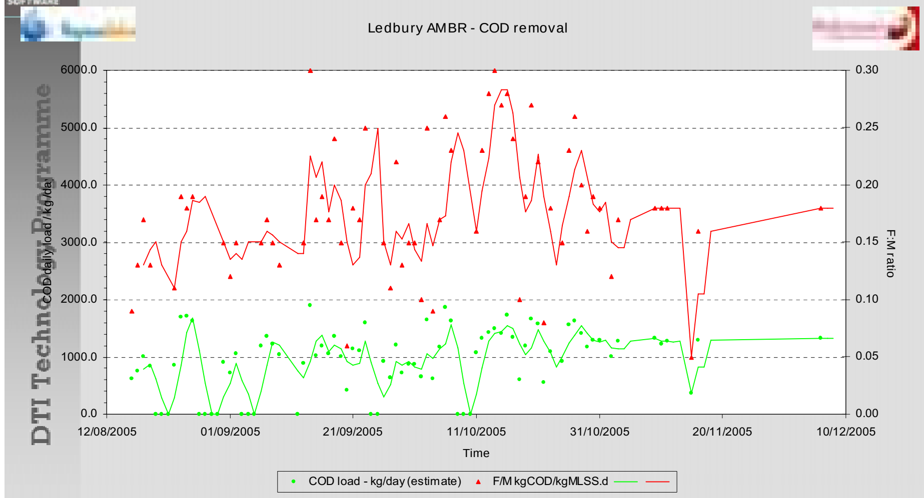
- Influent & sludge characterisation
- Detailed evaluation of flow scheme (design docs, existing process scheme & current oper. Mode)
- Tailor made sampling programme
- Ideally not based on complex batch / respirometric tests
- Use static data (steady- state) for mass balancing of COD, N & P
- Adjustment of kinetic parameters if necessary
- Model validation on other data

DTI Technology Programme

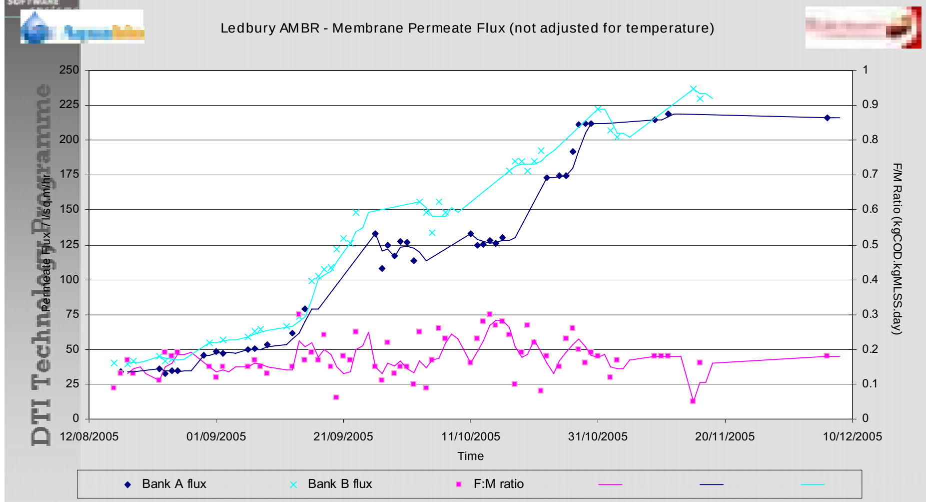
Robertson's Ledbury plant historical data



DTI Technology Programme

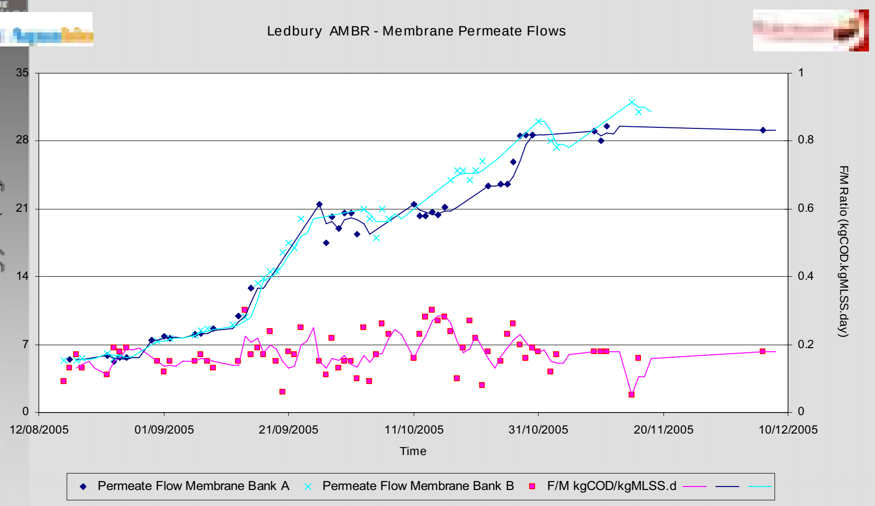


DTI Technology Programme



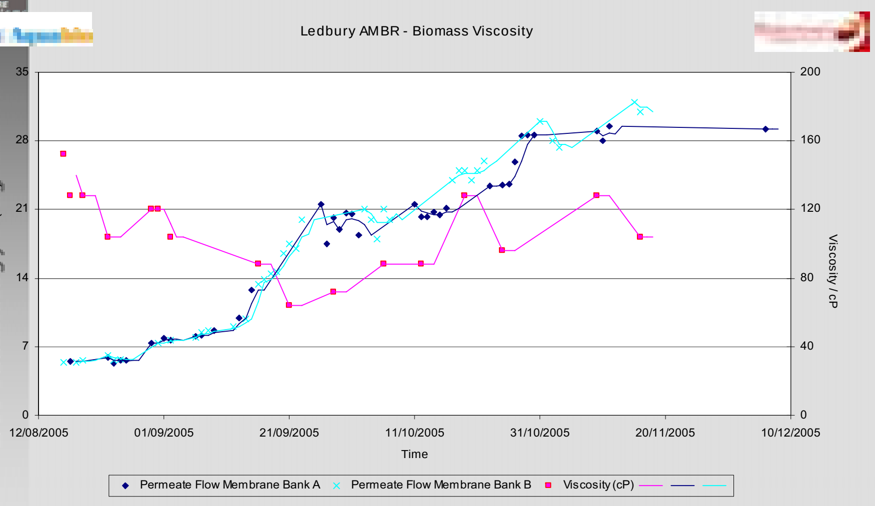
DTI Technology Programme

DTI Technology Programme



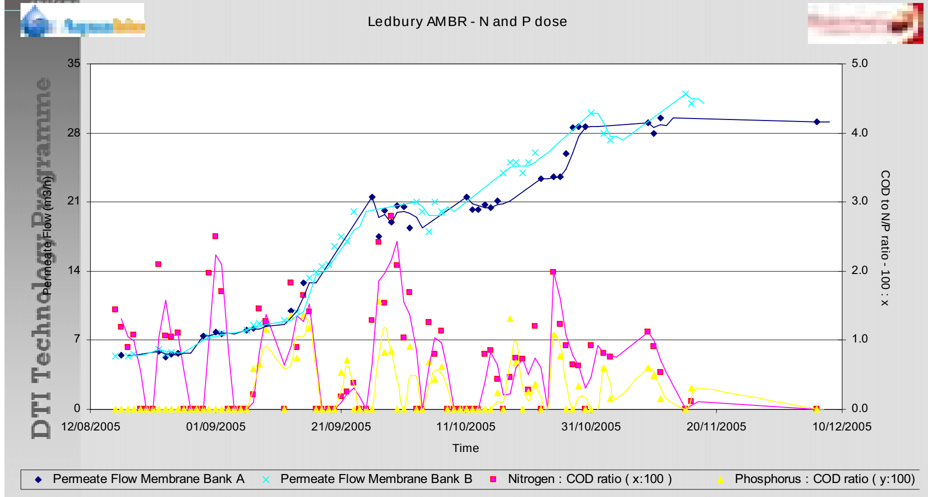
EUROMBRA WORKSHOP

DTI Technology Programme



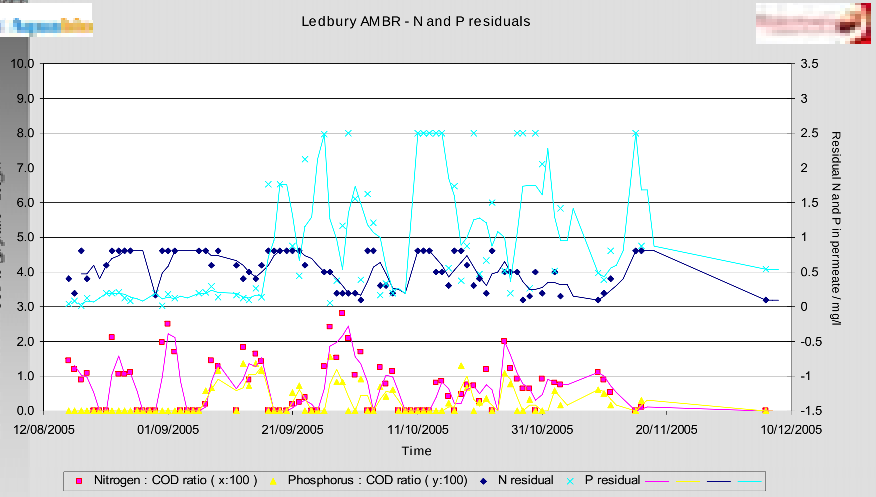
EUROMBRA WORKSHOP

DTI Technology Programme

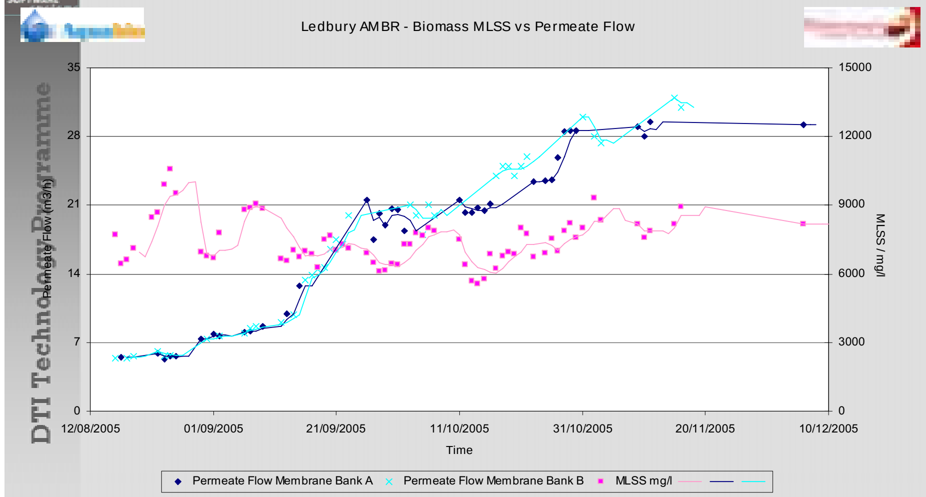


EUROMBRA WORKSHOP

DTI Technology Programme



EUROMBRA WORKSHOP


Ledbury AMBR - Biomass MLSS vs Permeate Flow

Finally……

- If you have any ideas, suggestions, ways forward in this research area, then please speak to me afterwards.

Many thanks for listening!

UNIVERSITEIT GENT

BIOMATH

Department of Applied Mathematics,
Biometrics and Process Control

Modeling the performance (effluent quality and membrane fouling) of a membrane bioreactor

Veerle De Schepper

Tao Jiang, Rik Danieels, Ingmar Nopens, Peter Vanrolleghem

12 July 2006

Ugent-BIOMATH, Coupure Links, 653, 9000 Ghent, Belgium
(email: Veerle.DeSchepper@biomath.ugent.be)

Overview

1. BIOMATH goal
2. Labscale reactor
3. Particle sizing
4. SMP – Fouling
5. Conclusions

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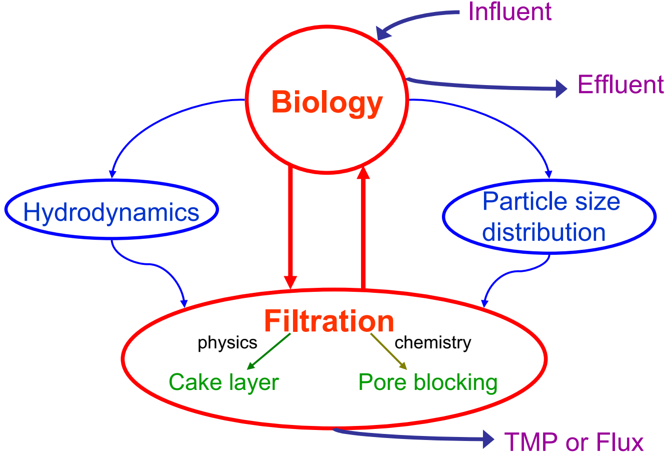
1. BIOMATH goal

Integral Mechanistic Model



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1. BIOMATH goal

Build a model

Calibration and validation

Experimental data

Labscale MBR

measurements { online
offline

Overview

1. BIOMATH goal
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4. SMP – Fouling
5. Conclusions

---

2. Labscale MBR

Bioreactor → **Anaerobic**

Bioreactor → **Aerobic**, **Anoxic**

---

2. Labscale MBR

Bioreactor

Membrane

-side stream

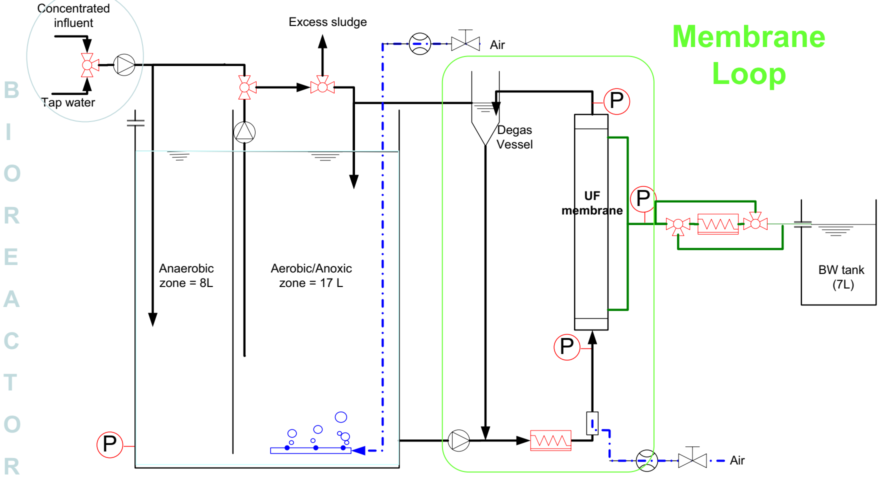
-tubular: X-flow (Norit)

-pore size: 30 nm

Effuent/Backwashing Tank

---

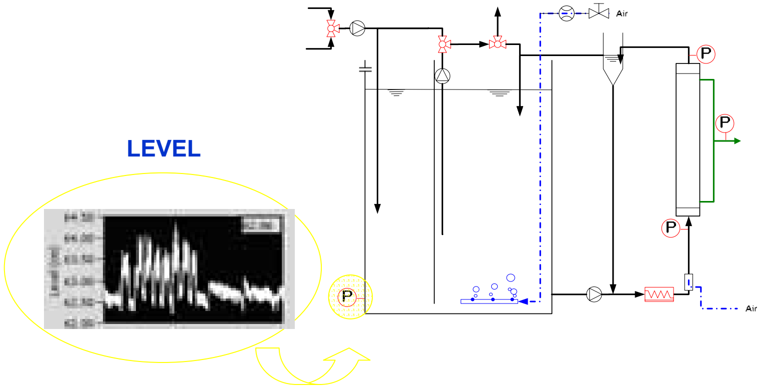
2. Labscale MBR



2. Labscale MBR

Online measurements:

Pressure sensors



LEVEL

Used for level control

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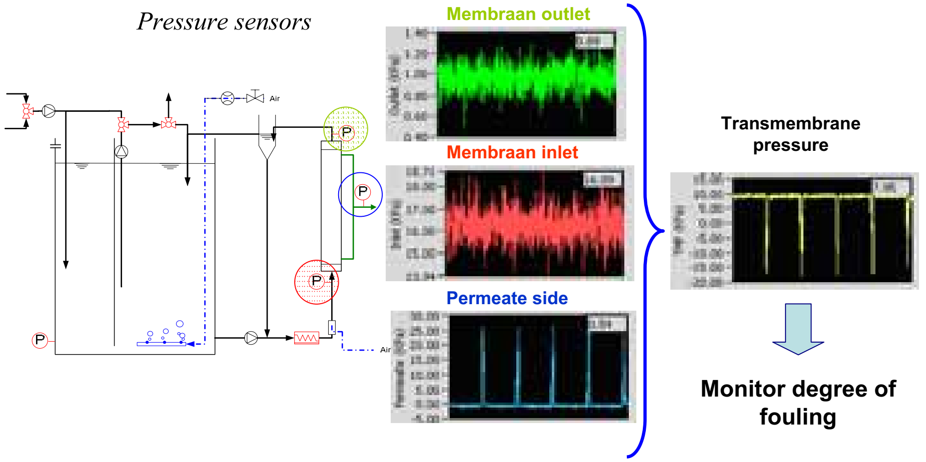
2. Labscale MBR

Online measurements:

Pressure sensors



Membraan outlet

Membraan inlet

Permeate side

Transmembrane pressure

Monitor degree of fouling

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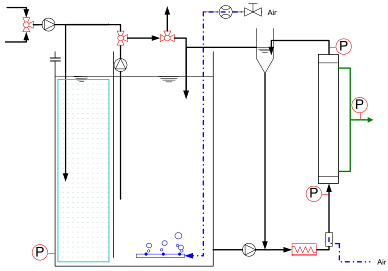
2. Labscale MBR

Online measurements:

Sensors: process parameters

Anaerobic

pH



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2. Labscale MBR

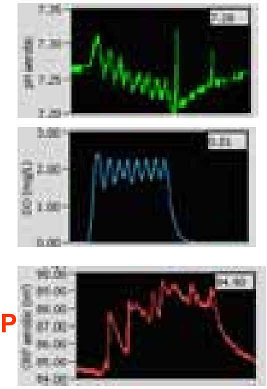
Online measurements:

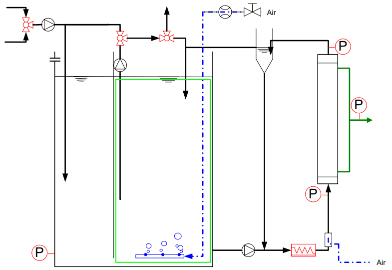
Sensors: process parameters

pH

DO

ORP





Aerobic/Anoxic

2. Labscale MBR

Offline measurements:

Effluent

-COD; BOD
-TN; NO3-N; NO2-N; NH4-N
-TP; PO4-P
-SMP = proteins + polysaccharide + COD

Activated sludge (bioreactor + membrane loop)

-MLSS; MLVSS
-SMP = proteins + polysaccharide + COD
-EPS = proteins + polysaccharide + COD
-microscopy
-viscosity

Overview

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---

3. Particle sizing: technics

Ligth scattering devices:

scattering pattern

⇩

size distribution

\+ Broad range

⇨ 0.04 µm to 2,000 µm

Examples: Mastersizer, Beckman Coulter, ...

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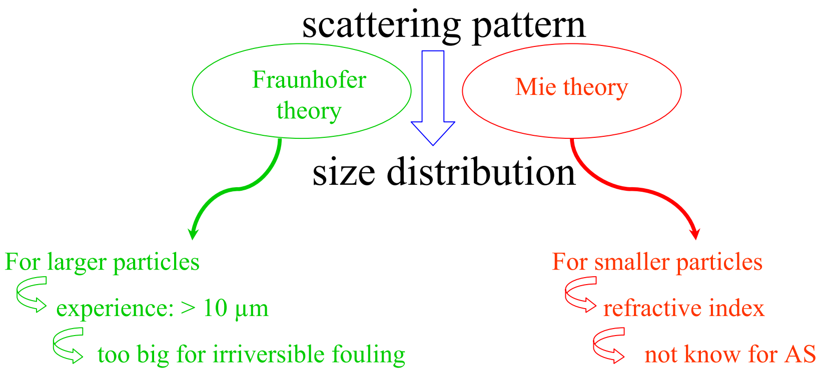
3. Particle sizing: technics

Disadvantages:



scattering pattern

Fraunhofer theory

Mie theory

size distribution

For larger particles

experience: > 10 µm

too big for irriversible fouling

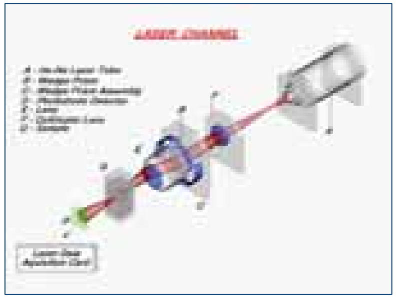
For smaller particles

refractive index

not know for AS

3. Particle sizing: technics

CIS-100
(ANKERSMID)



TOT

Image analyse

Not based on scattering pattern

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3. Particle sizing: technics

TOT

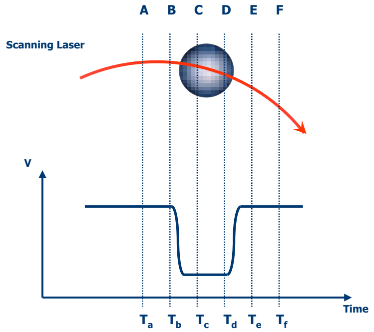
+ no refractive index

- small range: > 1µm

- dilution needed

  ↪ permeate

- air bubbles



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3. Particle sizing: technics

Image analysis

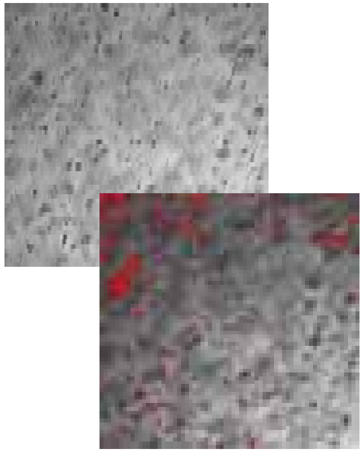
+ no refractive index

- small range: > 10µm

- dilution needed

  ↪ permeate

+ air bubbles eliminated



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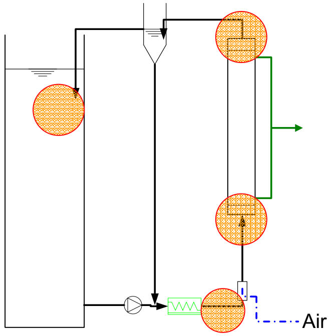
3. Particle sizing: data

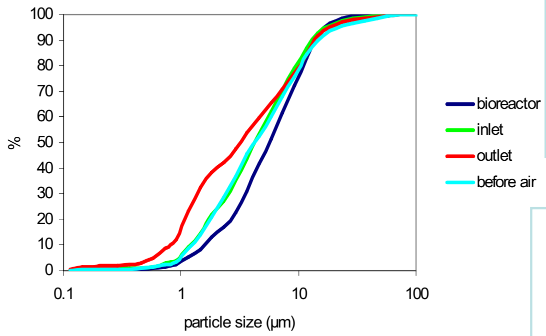
PSD measured at different places:



1. Bioreactor (+ air)
2. Inlet of the membrane (+ air)
3. Outlet of the membrane (+ air)
4. After recirculation pump

3. Particle sizing: data

TOT



PSD in bioreactor is shifted

⇩

breakage flocs in the membrane loop

PSD inlet >PSD outlet

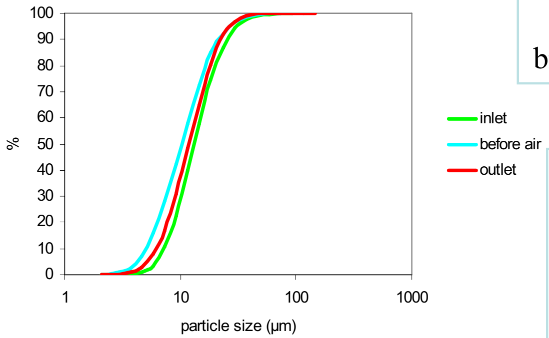
⇩

breakage flocs in membrane

---

3. Particle sizing: data

Image analysis



PSD inlet >PSD outlet

⇩

breakage flocs in membrane

PSD difference is smaller

⇩

Smaller particles are not measured as well as with TOT

Overview

1. BIOMATH goal
2. Labscale reactor
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4. SMP – Fouling
5. Conclusions

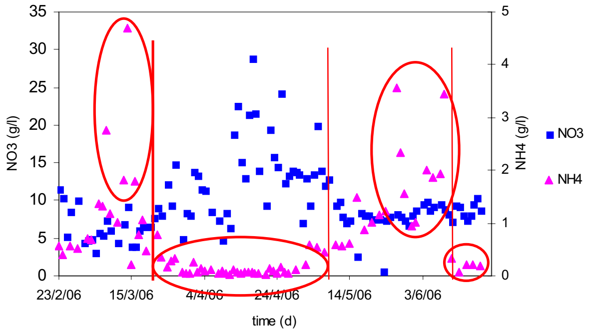
---

4. SMP – Fouling

2 PROBLEMS:

1) Bad nitrification: too much NH4+

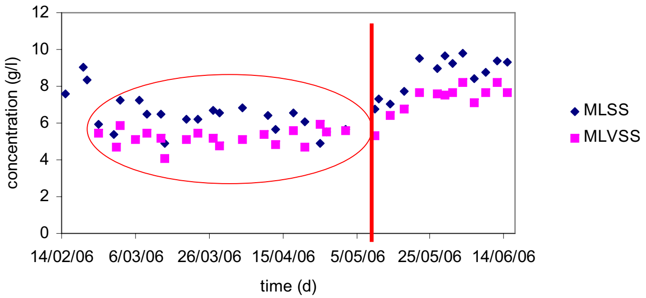
⟲ Oxygen increase (1 → 2 mg/L)



4. SMP – Fouling

2) Settling particulate influent in tubes

increased speed (recirculation)



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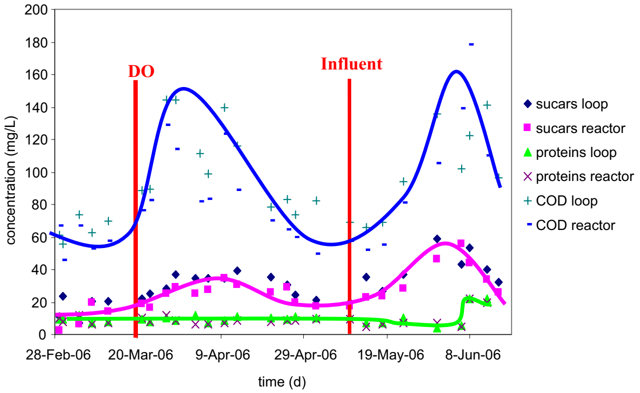
4. SMP – Fouling

Fixing the 2 problems

Influenced SMP concentration



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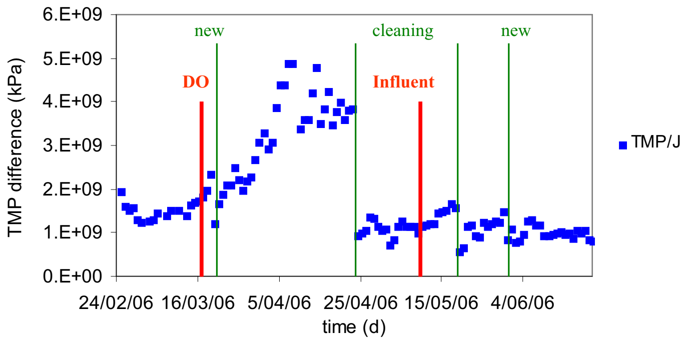
4. SMP – Fouling

Influence SMP on fouling

not straightforward



Overview

1. BIOMATH goal
2. Labscale reactor
3. Particle sizing
4. SMP – Fouling
5. Conclusions

5. Conclusions

- Labscale reactor: stable
  - collect data for model calibration
- PSD
  - instruments not optimal
  - small changes at different places
- SMP – Fouling relationship
  - not straightforward

Disscusion points

Particle size distrubution

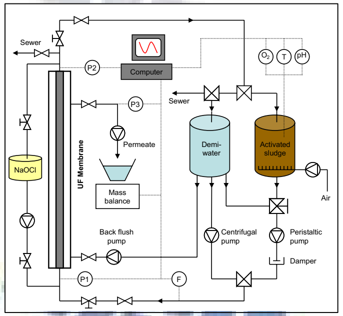
- which technics to use?

SMP- fouling

- what can cause the different fouling behavior?

Thank you for your attention!

The Delft Filtration Characterisation Installation



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Outline

- Fouling research approach DUT
- Delft Filtration Characterisation Installation
- Measuring protocol
- Output
- Possible applications
- Results

Fouling research

Membrane fouling:
still the biggest problem restricting application of MBR technology

- difficulty in fouling research: every single MBR has:
- unique influent properties
- unique biomass operation
- unique membrane operation

→ **Every MBR has a unique fouling process**

→ **Specific research results can not be generalized**

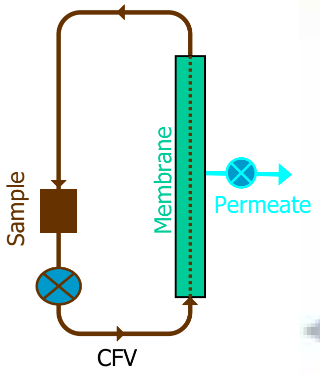
Fouling / Filtration

What are the filtration characteristics of the liquid to be filtered ?

Approach by TU Delft

- Work with real MBR installations and real (municipal) wastewater and activated sludge
- Find a way to make a **standardised comparison** of the filtration properties of different activated sludge samples / MBR installations
- Delft Filtration Characterisation Installation = **DFcI**

Delft Filtration Characterisation Installation (DFcI)



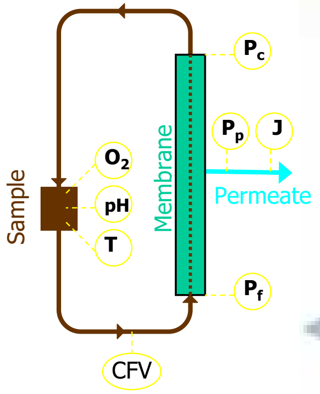
Membrane:

- -flow, tubular (side stream), single tube
- UF: nominal pore size 0.03 μm
- = 8 mm
- L = 95 cm

Sample:

- 30 litre MBR activated sludge
- recirculation with peristaltic pump
- constant cross-flow velocity: 1.0 m/s
- permeate extraction with peristaltic pump

Filtration Characterisation Installation (FCI)



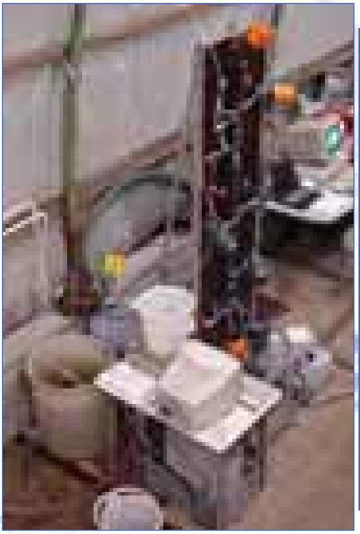
Monitoring:

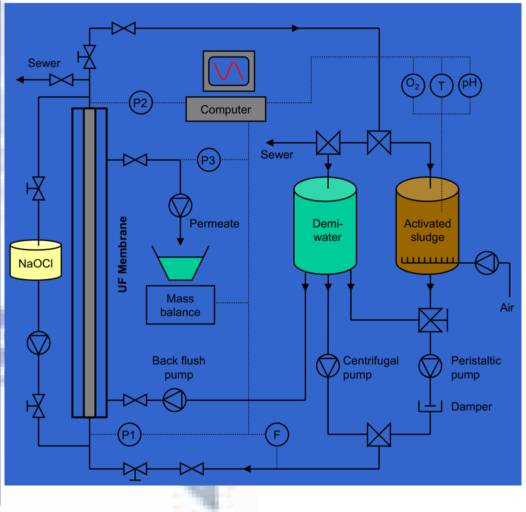
- sludge:
  - pH, temperature, oxygen concentration
- process:
  - cross-flow velocity, Flux
  - pressures $_{\text{feed, concentrate, permeate}}$ → TMP

Filtration Resistance: Darcy's law

→ $R = TMP / (\eta \cdot J)$

Delft Filtration Characterisation Installation

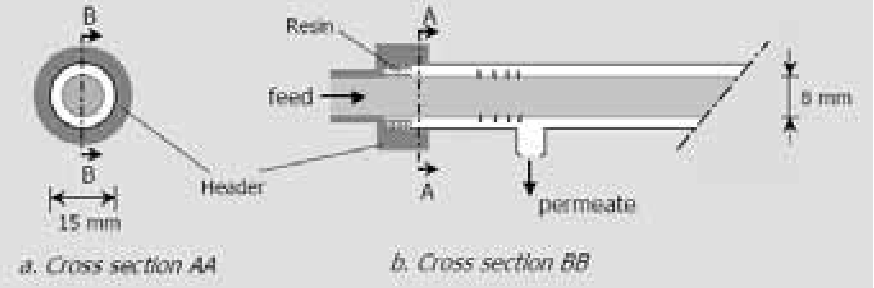




Membrane details

Header reduced to same diameter as membrane tube:

→ Undisturbed flow in the membrane tube



a. Cross section AA

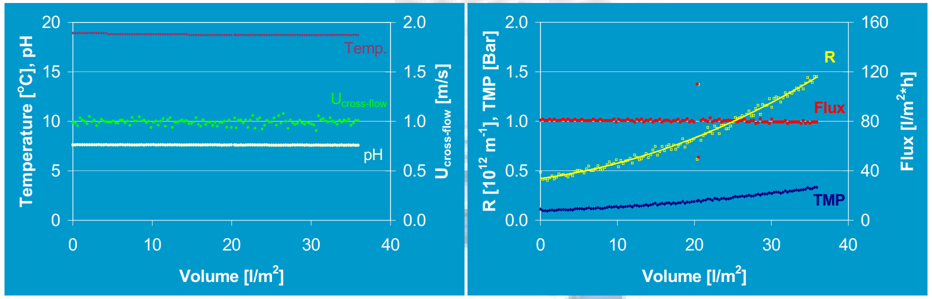
b. Cross section BB

Measuring protocol

1. Demi-water filtration (CFV=1.0 m/s, J=80 l/m²·h)
   - → check membrane resistance
2. **Sludge filtration** (CFV=1.0 m/s)
3. Membrane cleaning
   - → forward flush (4 m/s)
   - → back flush (-0.6 bar)
   - → chemical cleaning (NaOCl, 500 ppm)

Output: example

- constant temperature, CFV, pH and flux
- increasing TMP and resistance



Summary

- Short-term experiment (15 minutes)
- Output: Filtration curve

  → Comparison with sludge quality parameters:

  - ✓ EPS concentration (free water)
  - ✓ Suspended solids concentration / Viscosity
  - ✓ Particle size distribution

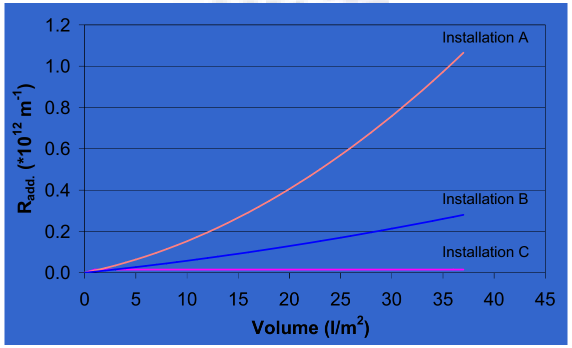
Application possibilities

- Monitor (dynamic) changes in filterability within one MBR installation over a longer period
- Compare different MBR installations
- testing filterability at different places in the reactor
- Batch tests in combination with sludge filterability manipulation (addition of COD, toxic substances,)

→ In combination with sludge quality analyses

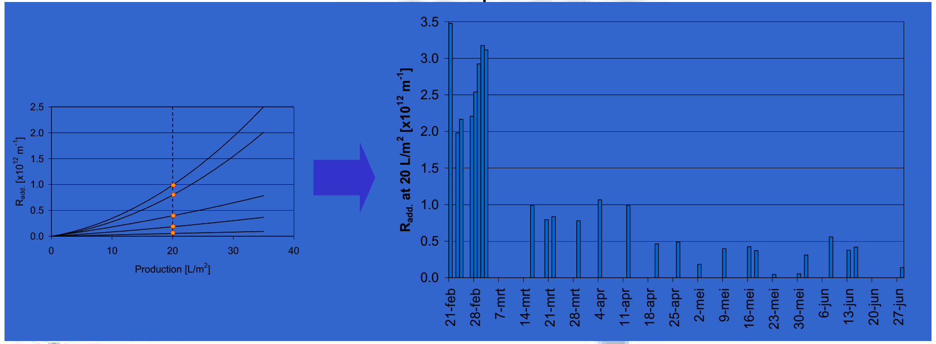
Comparison 3 pilot MBRs

- Three installations compared (10 consecutive days, 3 measurements per day)
- J=80 L/m^2*h
- Considerable differences between sludge filterability



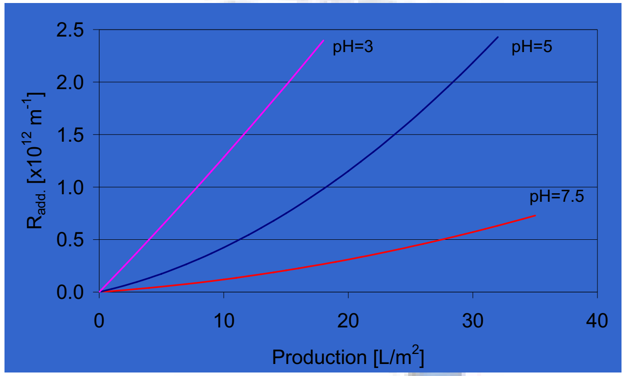
Long-term filterability monitoring

- One installation, sampling (at least) once per week
- J=80 L/m^2*h
- monitor additional resistance at production = 20 L/m^2



Batch tests

- Filterability manipulation by acid addition to activated sludge



Conclusions

Delft Filtration Characterisation Installation:

- reliable
- short-time
- standardised

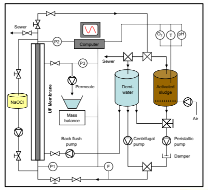
comparison method for filterability and fouling properties of (wastewater) activated sludges

- easily applicable (also in practice on full scale MBR s)

Acknowledgement

DISCUSSION

Comparison between Filtration Characterisation test results and full-scale performance of MBR Varsseveld



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Outline

- MBR Varsseveld
- Research approach
- Filtration Characterisation results
- Full-scale permeability
- Conclusions

MBR Varsseveld characteristics

- First Dutch full-scale MBR
- 23.000 p.e.
- Max. flow: 755 m^3/h
- Operational since the beginning of 2005
- Carrousel for biological treatment
- Zenon submerged UF membranes
- 4 separate membrane tanks

Research approach

- In a period of ten months 12 times activated sludge was sampled from one of the membrane tanks:

→ Filtration Characterisation

→ Comparison with full scale permeability data

link full-scale permeability over a longer period with results of short term filtration characterisation experiments

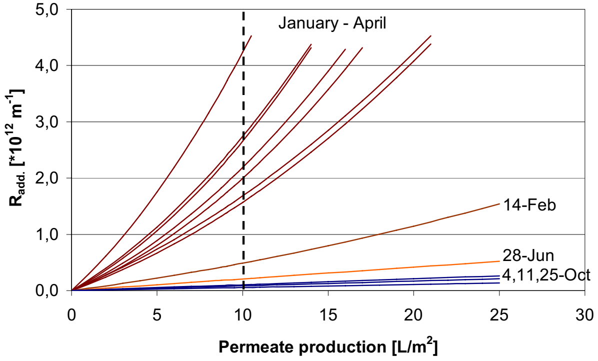
→ Fractionation and sludge quality analyses to identify foulants

Differences in filtration processes

Differences between the filtration process of the Filtration Delft Characterisation Installation (DFcI) and MBR Varsseveld:

	DFcI		**MBR Varsseveld**
→	Side-stream (cross-flow)	vs.	Submerged (air-scouring)
→	High flux (60 L/m²·h)	vs.	Low fluxes (15-35 L/m²·h)
→	X-flow (0.03 µm)	vs.	Zenon (0.04 µm)

Filtration Characterisation results



- CFV = 1.0 m/s
- J=60 L/m²·h
- Bad filterability in the period January – April
- Relatively positive exception on February 14th
- Major improvement as from June 28th
- Excellent filterability in October

MBR Varsseveld situation

- Severe fouling problems encountered in the first few months after the start-up
- The wastewater from a local cheese factory, containing the cheese covering polymer PVA (poly vinyl acetate), was suspected to be responsible for the fouling

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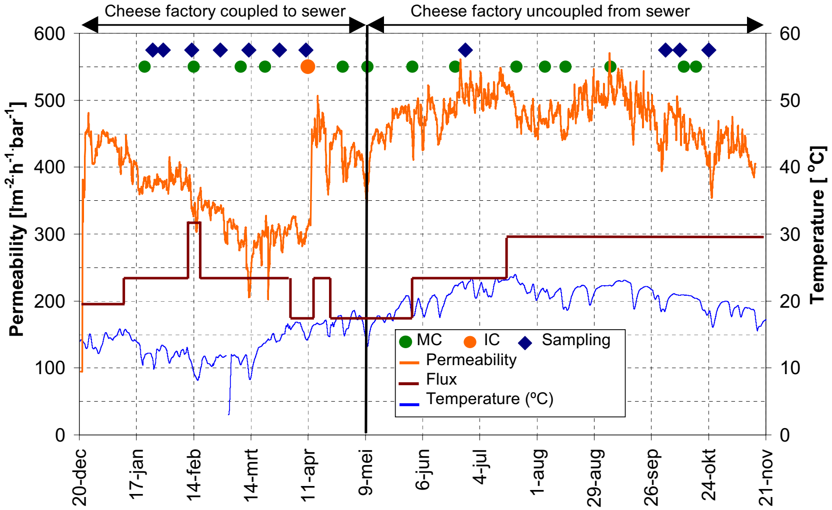
Cheese wrapping material

- Simulation Unit tests confirmed responsibility of PVA for the problems

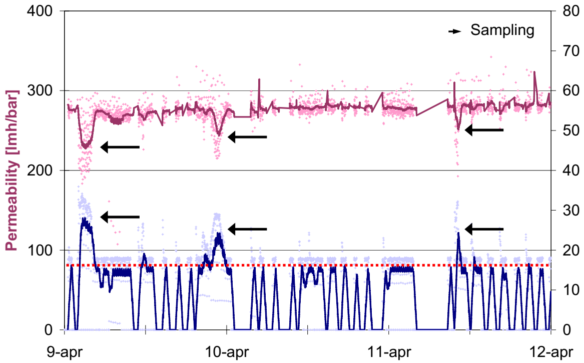
  → The cheese factory waste water was disconnected from the sewer as from the 9th of May 2005

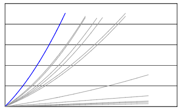
Full-scale permeability (MT2)



April 11th

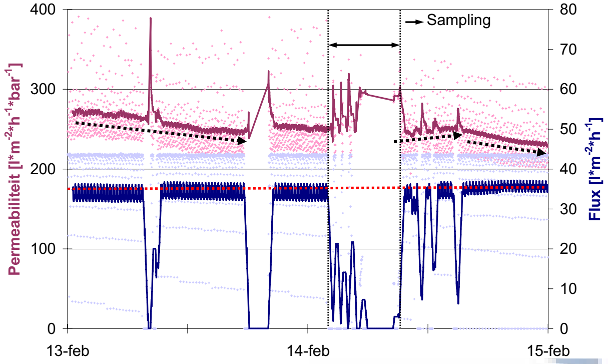
- Worst filterability as measured with the DFcI ever
- Bad filterability confirmed by full-scale permeability data: severe decrease for fluxes >20 L/m²·h

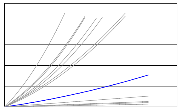




February 14th

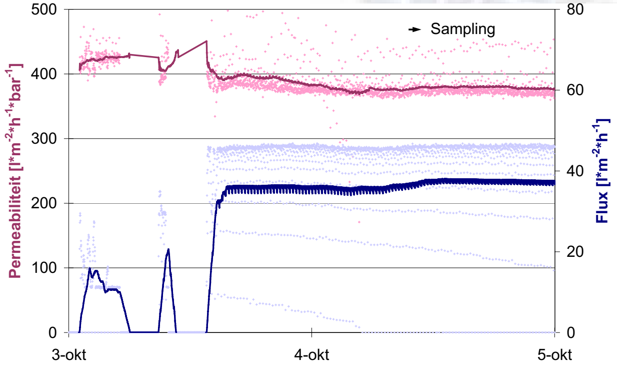
- Relatively good filterability as measured with the FCI
- No permeate extraction several hours prior to sampling: recovery full-scale permeability!

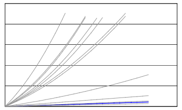




October 4th

- Excellent filterability as measured with the FCI
- Good permeability: despite high flux (capacity test), no decrease in permeability





Conclusions

- Split between Filtration Characterisation results before and after uncoupling a local cheese factory from the system
- Difference in filterability confirmed by full-scale permeability data

Filtration Characterisation seems to offer a good method to assess the filterability of a given activated sludge sample tapped from a pilot- or full-scale MBR installation with a short term experiment

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Acknowledgement

DISCUSSION